CA8160

Georgia Institute of Technology
Office of Contract Administration
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Project #: E-16-N94 Cost share #: E-16-393
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Contract #: NAG8-1417 Award type: GRANT
Prime #: Contract entity: GTRC
Contract type: CRNF

CFDA: N/A
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Project unit: AERO ENGR Unit code: 22
Project director(s):
PDPI- OLDS J R AERO ENGR (404)894-6289

Sponsor : NASA/MARSHALL SPACE FLT CTR, AL
Division Id: 105 / 3385
Award period: 15-OCT-1997 to 14-OCT-1998 (performance) 14-JAN-1999 (reports)

Sponsor amount	New this change	Total to date
Contract value:	25,000.00	25,000.00
Funded:	25,000.00	25,000.00
Cost sharing amount:	15,000.00	15,000.00

Does subcontracting plan apply? N

Title: COSTING & ECONOMICS FOR ADVANCED LAUNCH VEHICLES

PROJECT ADMINISTRATIVE DATA

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Phone:
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Security class (U,C,S,TS): U
Defense priority rating : N/A

ONR resident rep is ACO (Y/N): N
Supplemental sheet: N/A

Equipment title vests with: GIT

Administrative comments -
Initiation of research grant. GIT must cost share in the amount of $15,000 as a condition of this grant.

Georgia Institute of Technology
Office of Contract Administration
PROJECT CLOSEOUT - NOTICE

03-DEC-1998 14:17

Closeout Notice Date 03-DEC-1998

Project Number E-16-N94

Doch Id 48228

Center Number 10/24-6-R0779-0A0

Project Director OLDS, JOHN

Project Unit AERO ENGR

Sponsor NASA/MARSHALL SPACE FLT CTR, AL

Division Id 3385

Contract Number NAG8-1417

Contract Entity GTRC

Prime Contract Number

Title COSTING & ECONOMICS FOR ADVANCED LAUNCH VEHICLES

Effective Completion Date 14-OCT-1998 (Performance) 14-JAN-1999 (Reports)

Closeout Action:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	
Final Report of Inventions and/or Subcontracts	Y	
Government Property Inventory and Related Certificate	Y	
Classified Material Certificate	N	
Release and Assignment	N	
Other	N	

Comments

Distribution Required:	
Project Director/Principal Investigator	Y
Research Administrative Network	Y
Accounting	Y
Research Security Department	N
Reports Coordinator	Y
Research Property Team	Y
Supply Services Department/Procurement	Y
Georgia Tech Research Corporation	Y
Project File	Y

NOTE: Final Patent Questionnaire sent to PDPI

~~#1~~ → N/A
(NEW)

NASA Grant Progress Report

NAG8-1417

February 13, 1998

Jeff Whitfield - Georgia Institute of Technology

Research Sponsored By:

NASA - Marshall Space Flight Center

Engineering Cost Office

Research Goals

- Implement CABAM enhancements
  - develop new financing options
  - update to version 5.5 (bug fixes)
- Perform risk assessment research with CABAM
  - initially examined market volatility

CABAM Enhancements (v5.5)

- Developed new equity options
  - User inputs:
    - selects frequency of equity financing
    - selects number of times equity market accessed
    - enters amount of equity capital obtained
- Developed new debt options
  - User inputs:
    - selects between level coupon bonds and zero coupon bonds
    - selects frequency of debt financing

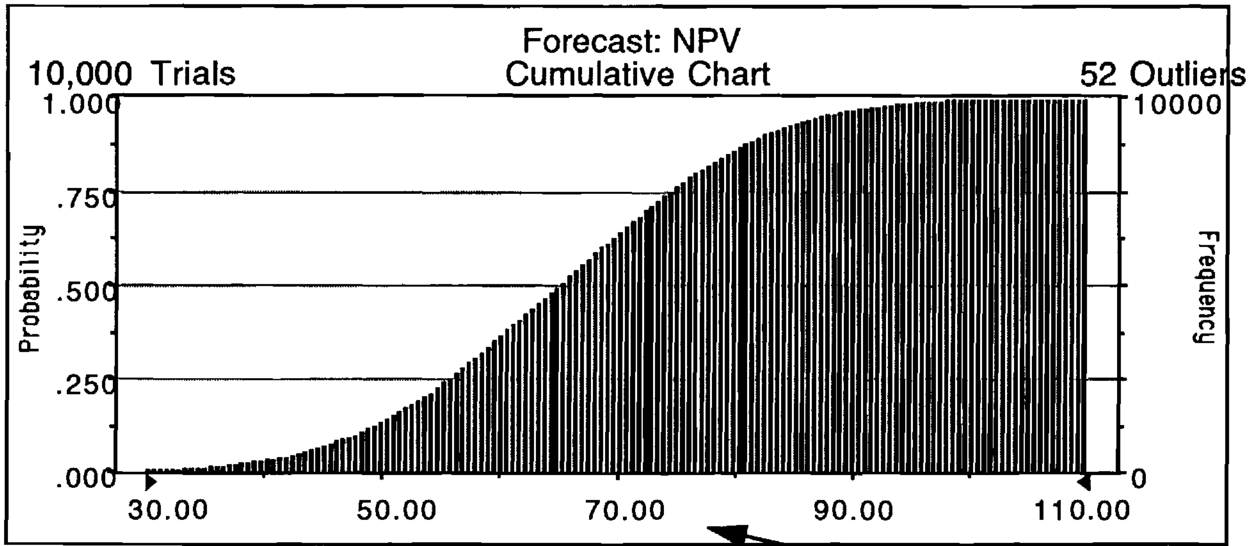
CABAM Enhancements (cont.)

- Corrected year orientation
- Removed late penalty
- Removed debt to equity ratio
- Corrected tax credit
- Added cash flow statement

Risk Assessment Research

- Varied the market size in a sample economic simulation scenario (Hyperion)
  - Commercial & Government
  - +- 15% variability
- Developed a response surface equation
- Performed a Monte Carlo Simulation
- Evaluation criterion selected was NPV
- Positive results attained

Cumulative NPV Distribution



NPV in $M ('96)

- Preliminary Uncertainty Analysis Results for NPV
  - mean NPV ~ $66M ('96)
  - 100% chance of positive NPV in this scenario (Hyperion)
  - 2σ range low = ~32M, high ~$110M

E-16-N94
#1

Final Report for
NASA Grant NAG8 – 1417

entitled

Cost and Economics for Advanced Launch Vehicles

Jeff Whitfield
Dr. John R. Olds (PI)
Georgia Institute of Technology
School of Aerospace Engineering

Period of Performance: Oct. 15, 1997 to Oct. 14, 1998

Georgia Institute of Technology

School of Aerospace Engineering
Atlanta, Georgia 30332-0150 U.S.A.
PHONE 404-894-3000
FAX 404-894-2760

November 20, 1998

Mr. Joe Hamaker
Head, Engineering Cost Office
Mail Code PP03
NASA Marshall Space Flight Center
Huntsville, AL 35812

Dear Mr. Hamaker,

Attached please find the final report for NASA Grant NAG8-1417 conducted at the Georgia Institute of Technology's Space Systems Design Laboratory during the period October 14, 1997 to October 14, 1998. I have also included a summary of activities completed under the grant and a copy of an AIAA technical paper produced.

Thank you for the opportunity to work with you on this grant. Your support has been critical to helping us build our cost estimating capability within the lab. Using the tool developed and improved under this grant (CABAM), we have been able to support a number of related NASA Marshall projects including Space Solar Power and Bantam-X. In addition, the research supported directly by this grant in the area of modeling economic uncertainty (primarily market size) and vehicle component weight uncertainty has been well received by the parametric cost estimating community.

We intend to continue to pursue improvements to CABAM and to continue our work to integrate cost estimating and economic simulation into our graduate curriculum. Thanks to the trailblazing support provided by this grant, I have received a number of inquiries from new students interested in joining our design group as economic specialists. I look forward to working with you and your organization on related projects in the future.

Sincerely,

Dr. John R. Olds
School of Aerospace Engineering
Director, Space Systems Design Lab
Georgia Institute of Technology
Atlanta, GA 30332-0150
404-894-6289
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Final Summary of Grant Activities

Grant NCC8 –1417, NASA – Marshall Space Flight Center

For the period October 15, 1997 – October 14, 1998

Grant Background:

This final report summarizes the activities and accomplishments of Georgia Tech's Space Systems Design Laboratory (SSDL) under NASA Grant NAG8-1417 from the Marshall Space Flight Center. The period of performance of the grant was October 15, 1997 to October 14, 1998.

At the beginning of this activity, both Georgia Tech and NASA's Engineering Cost Office recognized the need for 1) new economic modeling tools for advanced launch vehicle design and 2) a source for new engineers trained to understand the role of parametric cost modeling and economic impacts in design. In recent years, advanced space transportation has shifted from paradigm of the government as launch vehicle developer, operator, and primary customer to one driven by private enterprise (e.g. Kistler, Pioneer Rocketplane) or partnerships between private enterprise and government (X-33 and X-34). In this "new way of doing business", vehicle performance often takes a back seat to cost and overall economic payoff. The new vehicle system must be designed to be competitive in a commercial market while returning an attractive rate of return and overall profit to its investors.

To achieve this economic goal, vehicle designers must be able to estimate relative economic performance differences between design alternatives early in the design process. Georgia Tech's spreadsheet model CABAM – Cost and Business Analysis Module – has been in development since 1996. CABAM allows conceptual designers to estimate non-recurring costs (DDT&E, production, facilities), recurring costs (operations, propellant, labor, insurance, LRU's), and financing costs associated with a new launch vehicle venture. This Excel spreadsheet has been developed by Aerospace Engineering graduate students in the Space Systems Design Laboratory at Georgia Tech, and has been made available to various advanced design organizations throughout the United States. From 1996 – 1997, development was directly supported by NASA – Langley Research Center. In October 1997, CABAM was at version 5.0, but continued development required a new sponsor. NASA - Marshall agreed to support continued development.

Secondly, graduate aerospace engineering curricula and research programs in space vehicle design rarely include economic analysis as part of their core educational goals. As a result, engineering graduates are often poorly equipped to evaluate the cost and economic metrics associated with their new launch vehicle designs. Both NASA and Georgia Tech recognized the value of having a good conceptual cost estimating tool that can be used by students in engineering design project courses to learn basic cost estimating and economic analysis. In addition, the inclusion of a cost estimating "specialist" on Georgia Tech research projects could serve as a testbed for integrating cost estimating tools and analysis more closely with the traditional design disciplines of aerodynamics, propulsion, performance, etc. Integrating cost estimating more closely into integrated product design teams can demonstrate the improvements in vehicle economic performance to be had. In addition, having a research specialty in cost estimating provides a graduate research path for students interested in combining elements of aerospace vehicle design with economics.

Therefore, the mutual goals of Georgia Tech and NASA Marshall under this grant were

1) Continue to improve the current cost estimating spreadsheet CABAM. Add additional capabilities as needed, maintain compatibility with the most current versions of Microsoft Excel®, and perform maintenance to correct bugs, interface problems, etc.

2) Use CABAM as a teaching tool in the graduate design classes (here, Spacecraft and Launch Vehicle Design I and II). Train design students in the basics of cost estimating and economic modeling for advanced launch vehicles. Assign design problems where cost or economic performance variables (e.g. internal rate of return) are key outputs or constraints to the design process.

3) Support a cost-oriented aerospace engineering graduate student to represent the cost discipline on research design projects in the SSDL. Evaluate benefits and obstacles to integrating the cost and economics discipline more closely with the traditional design disciplines. Demonstrate the integration of economic analysis and vehicle design on a specific problem (here, evaluating the economic uncertainty associated with market and weight uncertainties in two candidate launch vehicle designs).

Major Accomplishments:

All three goals discussed above were accomplished within the period of performance of this grant.

First, CABAM was continually improved and re-released as CABAM v5.5 and later CABAM v6.0. The primary improvement was in the financial submodel. The cost analyst now has a wide choice of financing options including equity financing, zero coupon bonds, and level payment bonds. These options increase the tool's flexibility and usefulness for analyzing a variety on financing schemes for raising initial and sustaining capitol for a launch vehicle project. In addition, pro forma cash flow statements were added including annual cash flow, asset, liability, depreciation, revenue, and expense summaries. These statement sheets are consistent with annual report summaries and data produced in the business community and add a certain amount of universal "acceptance" to the data produced by CABAM.

In addition to these major updates, the user interface to CABAM was improved in a number of areas. For example, important summary data was collected and displayed on the Prog. Definition sheet. A new table summarizing government contributions to expenses was also created. Internal Rate of Return (IRR) and Net Present Value (NPV) were adjusted to be calculated based on free cash flow (revenue plus depreciation before subtracting interest and taxes) in constant year dollars in keeping with accepted practice in the business community. As a result, IRR's calculated in CABAM v5.5 or later do not include financing costs (interest payments). Thus an IRR of 25% must be evaluated by subsequently considering the interest expense of obtaining the necessary capital for the project. The updated version of CABAM was provided to MSFC's Scott May in August.

The second goal was to include CABAM as a teaching tool in the graduate space vehicle design classes at Georgia Tech. This was accomplished by instructing students in the use of CABAM during 2 three hour lab sessions in AE 6351C (Spacecraft and Launch Vehicle Design I). Subsequently, students were given a launch vehicle design project in which cost (here, just non-recurring cost) was a required output. In the following course, AE 6352C, the students formed an integrated design team to compete in the X-PRIZE University Design Competition. One student, Jeff Whitfield, served as the "cost specialist" for this team and used CABAM to predict development cost, production costs, facilities, revenue, and financing costs associated with the teams candidate space tourism vehicle design. *Polaris*. In March 1998, the *Polaris* design was judged to be the winning design by a panel of judges at the final competition review at MIT. This first place result was largely due to the strength of the economic and business analysis done on the design. The value of integrating economic analysis into the design was clearly demonstrated to the students on the team (and to the professor!).

For the third goal, a graduate student was directly supported by the project to conduct a research project in weight and economic uncertainty in launch vehicle design. The student was Jeff Whitfield. Jeff was a dual degree graduate student in Aerospace Engineering and Management. The results of his research project are documented in the final project report and the AIAA paper attached. As a quick summary, the project was to assess the economic risk that results for fluctuations in vehicle design weight (and therefore cost and payload) and fluctuations in expected market size (and therefore revenue). Two vehicle designs were evaluated using CABAM v5.5 and a Monte Carlo method for dynamically varying market and component weight inputs and recalculating IRR at each simulation. 5000 simulations were run for each vehicle to create a probability distribution of IRR for the overall simulation. Risk was defined as the standard deviation of the IRR (lower is better) and the overall reward-to-risk metric used to evaluate each simulation was the Sharpe Ratio. The results conclude that neither advanced concept evaluated had a sufficient Sharpe Ratio to attract investors! Both had too much risk and too little expected return (IRR). Uncertainty in the emerging commercial cargo market was a key source of risk. Uncertainty in the primary body structure weight was a second major source of risk as it influences payload and vehicle development and production costs.

Based on the success of Jeff's initial results and the analysis techniques he developed for his research project, this type of Monte Carlo reward-to-risk uncertainty analysis with CABAM has been included in the Design for Life Cycle Cost course (AE 4353) during the Fall 1998 quarter at Georgia Tech as one of the "space" oriented class projects. We expect this experience in economic risk assessment will be useful to engineering students throughout their careers.

In addition to his research, Jeff served as the cost specialist on a number of NASA-sponsored SSDL research projects including Space Solar Power and Bantam X. His role on these research programs have helped highlight the need for integrating cost into integrated design teams and have demonstrated the benefit of doing so. Two new graduate students applying for our research group have identified the "cost specialist" as one of the positions they are interested in.

Students Supported:

During the 1997 – 1998 academic year, one graduate student was supported directly by this grant (i.e. provided a monthly stipend and tuition)

1) Jeff A. Whitfield

During the period of performance, Jeff was enrolled in both the Master of Science in Aerospace Engineering and Master of Science in Management programs at Georgia Tech.

Degrees Awarded:

One advanced degree was awarded in the 1997 – 1998 academic year based partially on research work performed for this contract.

1) Jeff A. Whitfield, Master of Science in Management, June 1998.

After the completion of his MSM degree and the research associated with this grant, Jeff discontinued his pursuit of his MS AE degree in favor of an opportunity to begin his own business in private industry.

Travel:

The following travel was taken in support of activities related to this grant.

1) Dr. John Olds and Jeff Whitfield attended the 1998 Defense and Civil Space Programs Conference and Exhibit in Huntsville, AL on October 28 – 30 to present an AIAA paper on the results on the research conducted under this grant.

In addition, Mr. Eric Shaw of NASA – MSFC's Engineering Cost office visited Georgia Tech on Feb. 13, 1998 to deliver a presentation and discuss details of the project.

Papers Published & Presented:

One AIAA paper was published during this period of performance based on the supported research program. A copy of the paper is also included to this final report as an attachment.

1) Whitfield, J. A., and Olds, J. R., "Economic Uncertainty of Weight and Market Parameters for Advanced Launch Vehicles," AIAA paper 98-5197, 1998 Defense and Civil Space Programs Conference and Exhibit, Huntsville, AL, October 28-30, 1998.

Plans for Continuing Project:

Georgia Tech plans to continue its work in both the educational and research aspects of cost estimating and business modeling for advanced launch systems. A follow-on activity including this and other conceptual design improvement goals has been proposed to the Advanced Space Transportation Program (ASTP) office headed by Mr. Garry Lyles. This proposal is currently being evaluated.

Final Report for
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Cost and Economics for Advanced Launch Vehicles

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Period of Performance: Oct. 15, 1997 to Oct. 14, 1998

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1. ABSTRACT

Market sensitivity and weight-based cost estimating relationships are key drivers in determining the financial viability of advanced space launch vehicle designs. Due to decreasing space transportation budgets and increasing foreign competition, it has become essential for financial assessments of prospective launch vehicles to be performed during the conceptual design phase. As part of this financial assessment, it is imperative to understand the relationship between market volatility, the uncertainty of weight estimates, and the economic viability of an advanced space launch vehicle program.

This paper reports the results of a study that evaluated the economic risk inherent in market variability and the uncertainty of developing weight estimates for an advanced space launch vehicle program. The purpose of this study was to determine the sensitivity of a business case for advanced space flight design with respect to the changing nature of market conditions and the complexity of determining accurate weight estimations during the conceptual design phase. The expected uncertainty associated with these two factors drives the economic risk of the overall program.

The study incorporates Monte Carlo simulation techniques to determine the probability of attaining specific levels of economic performance when the market and weight parameters are allowed to vary. This structured approach toward uncertainties allows for the assessment of risks associated with a launch vehicle program's economic performance. This results in the determination of the value of the additional risk placed on the project by these two factors.

2. NOMENCLATURE

CABAM	Cost and Business Analysis Module
CER	cost estimating relationship
CSTS	Commercial Space Transportation Study
DDT&E	design, development, test, & evaluation
EBIT	earnings before interest and taxes
ESJ	ejector scramjet
HTHL	horizontal take-off, horizontal landing
IOC	initial operating capability
IRR	internal rate of return
LCC	life cycle cost
LEO	low earth orbit
LH2	liquid hydrogen
LOX	liquid oxygen
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Admin.
NASCOM	NASA Cost Model
NPV	net present value
RBCC	rocket-based combined cycle
RLV	reusable launch vehicle
ROI	return on investment
SSDL	Space Systems Design Laboratory
SSTO	single-stage to orbit
TFU	theoretical first unit
TRL	technology readiness level
VTHL	vertical take-off, horizontal landing

3. INTRODUCTION

With the advent of commercial space launch vehicles and the drive towards a balanced federal budget, government financial participation in the space launch industry has significantly declined. In order to finance new programs and facilitate the advancement of technologies necessary to travel in space, private capital investment is needed. The growth in market demand for launch services has attracted the interest of private investors. However, commercial investors require a high rate of return on their investments in order to take on the risk associated with these types of programs. In order to attain the necessary capital investment required to initiate new programs, it is essential that designers incorporate financial assessments into the conceptual design phase. These assessments not only need to include the economic outlook of the project, but also to include the risk associated with the assumptions made in the projection.

One methodology used in calculating the financial costs of advanced space launch vehicle designs employs parametric cost estimates. It has been determined that parametric cost estimates allow for greater speed, accuracy, and flexibility in performing these assessments than derived from using other estimating techniques.[1] Parametric cost estimates use cost estimating relationships (CER) and relevant mathematical algorithms to determine cost estimates.

A cost estimate is not expected to precisely predict the actual cost of a launch vehicle program, however it should provide a realistic basis for evaluating the project. The cost analyst should work towards the goal of "cost realism," which is a term used to describe the items that make up the foundation of the estimate. These include the logic used in developing the model, the assumptions made about the future, and the reasonableness of the historical data used in determining the estimate. By analyzing the effects of uncertainty inherent in the predicted value, the analyst is able to determine a more realistic view of the appropriateness of the results.

Parametric models have been developed for assessing the financial viability of advanced space vehicle launch programs. To create this type of model, certain simplifications must be made. These simplifications result in modeling uncertainties that translate into risk when trying to produce a realistic estimate of the financial feasibility of a project. This study analyzes and quantifies the risk associated with two of the assumptions made in performing this type of assessment. This includes the market variability of predicting future demand inherent in any commercial market and the uncertainty in determining accurate weight estimates.

4. TOOLS

The tools used in this research include CABAM (Cost and Business Analysis Module) and Crystal Ball. CABAM is a tool that utilizes parametric economic analysis to determine the financial feasibility of advanced space launch vehicles. Crystal Ball utilizes Monte Carlo simulation techniques to determine the possible outcomes when variability is introduced into the problem. By combining these two tools, an analysis of the effects of variability in weight and market parameters was completed.

4.1. Background on CABAM

CABAM was developed at Georgia Tech in response to the need to have a tool that provides a financial assessment of conceptual launch vehicle design. This tool incorporates not only the cost attributes associated with a project, but also identifies the potential revenue streams and projects several different evaluation metrics including net present value (NPV), internal rate of return (IRR), and return on investment (ROI).

CABAM is a Microsoft Excel workbook based simulation tool developed for the analysis of conceptual space launch vehicles. It requires the user to input basic launch vehicle system definitions through component weights and economic parameters such as inflation rate, interest rate, and tax rate. Since it only requires these basic inputs, CABAM may be used for an economic assessment at the conceptual design stage.

CABAM is a long-term launch program simulation tool that runs off of four main variable inputs: the launch price for each target market. It is a fiscal based analysis tool that utilizes fixed rates for all of its economic parameters for the entire life of the project. Yearly life cycle costs and revenue are generated to provide annual cash flows for the project being evaluated.

A schematic of the structure of CABAM is shown in Figure 1. CABAM has a modular structure that is divided into the major components of life cycle cost and revenue generation. The revenue side of CABAM is divided between the government market and the commercial market, which is then further subdivided between cargo and passenger markets. The life cycle cost side of the program is divided into three sections, non-recurring costs, recurring costs, and financing costs. The two major components, cost and revenue, are not dependent upon each other and can be generated separately.

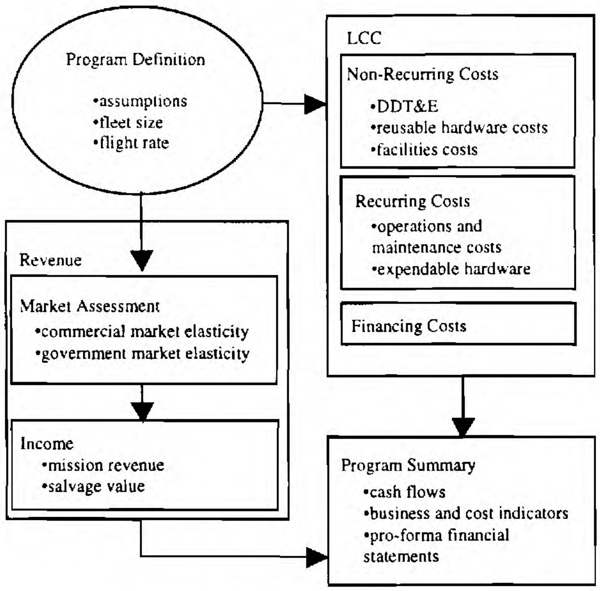


Figure 1: Structure of CABAM

CABAM utilizes elastic market models that were developed during the Commercial Space Transportation Study (CSTS) performed by NASA in 1994.[2] Once the launch prices are determined for each of the four markets, CABAM estimates the market share captured and determines the flight rate and required fleet size to accommodate that particular level of market penetration. From this information, yearly revenue streams are calculated.

CABAM separates life cycle costs into three sections, non-recurring costs, recurring costs, and financing costs. The non-recurring costs are determined through weight-based cost estimation relationships. Recurring costs are broken down into four components: airframe insurance, propellant, labor, and reusable hardware refurbishment. The financing costs are determined through the use of a bond scheme that provides the necessary capital for each year's cash flow requirements.

To determine the total non-recurring cost, CABAM first calculates the design, development, testing, and evaluation (DDT&E) and theoretical first unit (TFU) costs for reusable system components. Weight-based CERs are used to estimate the costs for the vehicle, which are broken down by major subsystems. The CERs are in the form of equation 1.[3]

$$\text{Cost (\$)} = A * W^B * C_f \qquad (1)$$

In the equation, W is the weight of each major component, A and B are constants and Cf is the complexity factor. The A and B values are system component-specific constants obtained from the unrestricted-release version of the NASCOM database for similar component groups.[4] The complexity factor is determined based upon the mechanical and material technology readiness of the components.

4.2. Enhancements to CABAM

During the past year, the Space Systems Design Lab (SSDL) at Georgia Tech has continued to upgrade CABAM. The most significant change made was the way in which the model calculates NPV and IRR. The fundamental change was to discount the "free cash flow" of the program, calculated in real dollars, by the real discount rate. This alleviates the problem of having to adjust all future cash flows by the expected inflation rate. The free cash flow is calculated by adding depreciation to earnings before interest and taxes (EBIT) and then subtracting capital investments. By using this method, interest is correctly accounted for in the discount rate and the effect of taxes is removed. This was done to simplify the process of using CABAM in performing a business analysis of an advanced space launch vehicle during the conceptual design phase.

A second major enhancement to CABAM was the addition of detailed pro-forma financial statements. This includes an income statement, a balance sheet, and a cash flow statement broken down by year for the entire life of the program. Along with these upgrades, the user was given greater flexibility in choosing options related to the financing of the program. Included in the newest version of CABAM is the option to use either level-payment bonds or zero coupon bonds. Also, the user now has the ability to include multiple equity investments made in the project.

4.3. Crystal Ball

Crystal Ball is a user-friendly, graphically oriented forecasting and risk analysis program that provides the probability of certain outcomes.[5] It utilizes Monte Carlo simulation techniques to forecast the entire range of results possible for a given situation. Crystal Ball also provides the confidence levels so that the user will know the likelihood of any specific event taking place. For these reasons, it was determined that this software package would be used for the research work.

A Monte Carlo simulation is a system that uses random numbers to measure the effects of uncertainty in a model. This is achieved by first specifying the probability distributions for all of the uncertain quantitative assumptions. Next, a random number is generated from the distribution for each parameter to arrive at a set of specific values for computing the output of the simulation run. This process is then repeated numerous times to produce a large number of output values. An approximation of the probability distribution of the output values may be obtained by breaking the range of values into equal increments and counting the frequency with which the trials fall into each increment. As the number of trials increases, the frequencies will converge toward the actual probability.[6]

5. ANALYSIS

By utilizing the Monte Carlo simulation technique, an analysis of the effects of allowing certain variables to vary within a predetermined range was possible. This study investigated the effects of allowing two variables, the market characteristics and weight estimates to vary within specified ranges to determine the effect on the economic viability of the project.

5.1. Calculating Weight Variability

The first step in setting up the analysis was to determine an appropriate methodology for fluctuating weight parameters during the simulation runs. The original weight included a 15% dry weight margin to allow for weight growth that normally occurs as the vehicle goes through the different stages of design. CABAM does not use this weight margin in its calculation of DDT&E or TFU. Therefore, if weight growth does not occur, the margin may then be used as additional payload capacity.

CABAM was reconfigured to allow for adjustments to be made in the size of the payload capacity depending on the total combined weight of the components in comparison to the original dry weight of the vehicle. Therefore, if the new weight of the vehicle exceeded the original weight, the difference was then subtracted from the payload capacity, thus reducing revenue for each launch. The opposite also held true: if the new weight was less than the original weight, then the payload capacity was increased resulting in additional revenue.

For passenger missions, incremental changes in the number of passengers carried per flight were only permitted for increments of 1800 lbs. It was assumed that each passenger would generate that amount of weight growth in the different systems required to transport a human into space.

Table 1: Variances by Component Group

Component Groups	Minimum	Maximum
Wing Group	-5%	20%
Tail Group	-5%	20%
Body Group	-5%	20%
TPS Group	-5%	20%
Landing Gear	-5%	20%
Main Propulsion	-5%	25%
RCS Propulsion	-5%	10%
OMS Propulsion	-5%	10%
Primary Power	-5%	10%
Electrical Conversion and Distribution	-5%	10%
Surface Control Actuation	-5%	10%
Avionics	-10%	10%
Environmental Control	-5%	10%

The weights of the different component groups listed in Table 1 were allowed to vary by the percentages shown in the table. Avionics was allowed to fluctuate equally on either side of the most likely estimate because of the continual evolution in the development of smaller electronic components compared to the normal weight growth that occurs with all components. The main propulsion was given the greatest allowance on the maximum side because of the complexity of developing new engines for advanced space flight launch vehicles. Structures were given a 20% growth allowance and subsystems were given a 10% growth allowance for the simulation runs.

As shown in Figure 2, a triangular distribution was placed on each of the component groups for the Monte Carlo simulation. The minimum and maximum weights allowed were calculated based upon the percentages listed in Table 1.

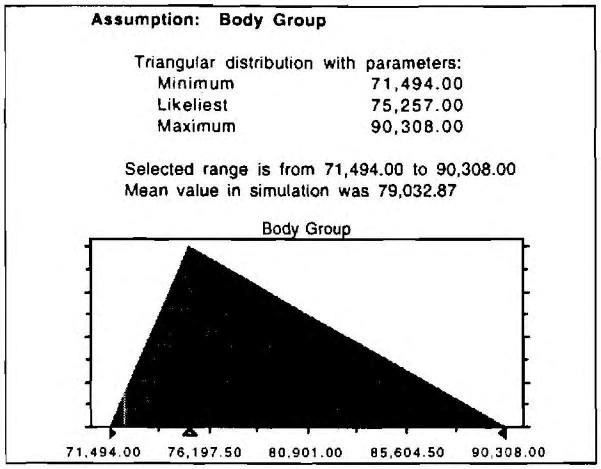


Figure 2: Representative Triangular Weight Distribution

5.2. Calculating Market Volatility

To evaluate the sensitivity of the model to changing market conditions, an approximation of the volatility of demand was assumed. The authors estimated that greater volatility exists in the lower price segments compared to that occurring in the higher price market. The reason for this estimation was based upon the fact that market demand is already known for higher price segments based upon current market conditions, thus lower risk exists for competing in this price range. As shown in Table 2, it was assumed that at the lower price segment, a 30% fluctuation in the size of the commercial market and a 15% fluctuation in the size of the government market may exist from current estimations. At the higher price segment, a 5% fluctuation was included for both markets.

Table 2: Prices and Market Fluctuation for Each Market Segment

	Price				Market Fluctuation	
Market Segment	Units	Optimal	High	Low	High	Low
Commercial Cargo	$/lb	820	5,000	100	30%	5%
Commercial Passengers	M$/passenger	0.52	5.0	0.2	30%	5%
Government Cargo	$/lb	1,650	5,000	100	15%	5%
Government Passengers	M$/passenger	7.12	15.0	0.2	15%	5%

Figure 3 shows the market estimations for commercial cargo, which is one of four markets used in this study. The solid line represents the baseline case and the long dash lines represent the variability possible in market demand. This graph depicts the tapering of market variability as the price increases.

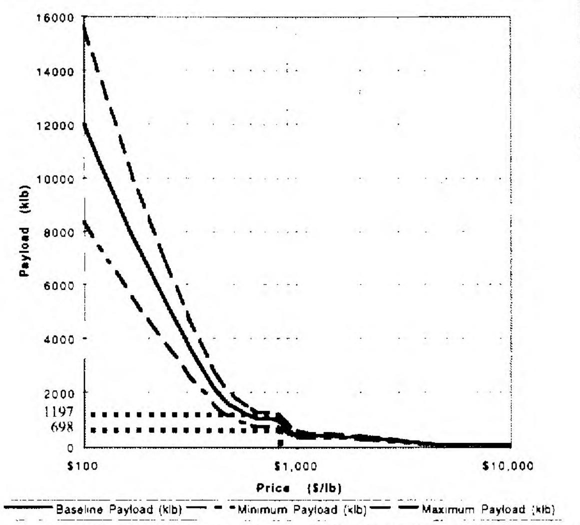


Figure 3: Commercial Cargo Market

Two equations were derived to determine the size of the market captured under the predefined assumptions. By using these equations, the market volatility was quantified for a specified price. For the commercial cargo market, the market demand fluctuated between 1,197,000 lb. and 698,000 lb. at a price of $820 /lb. as shown in Figure 3 by the horizontal dotted lines. The first equation gives the total demand in pounds for the market.

$$F * S * B + B = M \qquad (2)$$

In equation 2, F is the factor that is allowed to vary between 1 and –1 during the Monte Carlo simulation creating the effect of either being greater than or less than the expected value. As shown in Figure 4, a triangular distribution was placed on F for the simulation run. B is the base value of the market demand determined by the price. S is the scale factor that fluctuates between 5% and 30% for the commercial market and between 5% and 15% for the government market depending on the price. The result of this equation, M, is the net market size captured by the particular project under evaluation.

$$S = S_2 - \frac{S_2 - S_1}{P_2 - P_1} (P_2 - P) \qquad (3)$$

Equation 3 was used to calculate S for equation 2. P is the price to launch either a pound of payload or one person into low earth orbit (LEO). For each of the four market segments, the price was set at the optimal level to achieve the maximum rate of return for the program. A grid search optimization strategy was used to determine the optimal pricing strategy for this class of vehicles.[7] The prices used in the analysis are shown in Table 2. P1 is the price at the lower bound and P2 is the price at the upper bound. These bounds are represented by the high and low figures also shown in Table 2. S1 is the maximum fluctuation allowed in the market and S2 is the minimum fluctuation allowed. These percentages are also shown in Table 2.

Assumption: Commercial Cargo

Triangular distribution with parameters:

Minimum	-1.00
Likeliest	0.00
Maximum	1.00

Selected range is from -1.00 to 1.00
Mean value in simulation was 0.00

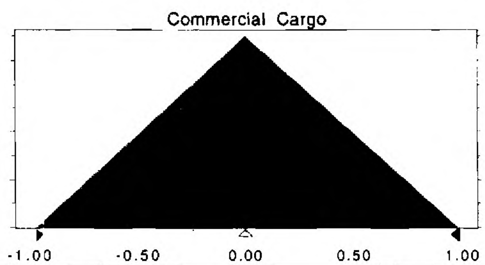


Figure 4: Representative Triangular Market Distribution

5.3. Sample Vehicles

To provide analysis data for this research, two candidate single-stage-to-orbit (SSTO) reusable launch vehicle (RLV) designs were chosen to serve as reference vehicles. For both designs, the initial operating capability (IOC) was projected to be 2008 and steady state operation was assumed for the period from the year 2010 to 2025. The baseline case for the two vehicles had a cargo capacity of 44,000 pounds or twenty-four passengers. Each vehicle was configured to allow for cargo and passenger service to low earth orbit (LEO).

The first concept selected, which takes advantage of more off-the-shelf technologies, was an SSTO vehicle with vertical take-off and horizontal landing (VTHL). This concept, which utilizes five LOX/LH2 rocket engines, is shown in Figure 5.

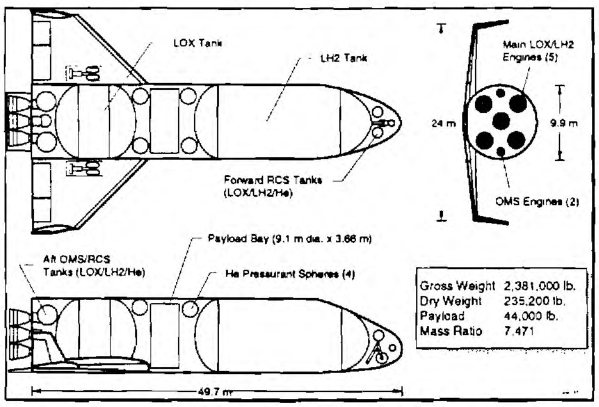


Figure 5: SSTO All Rocket Vehicle

The second concept, an advanced launch vehicle named "Hyperion," is currently being investigated by students in the SSDL at Georgia Tech. This concept, shown in Figure 6, represents an RLV with horizontal take-off and horizontal landing (HTHL). The propulsion system of this vehicle consists of five LOX/LH2 ejector scramjet (ESJ) rocket-based combined–cycle (RBCC) engines.[8]

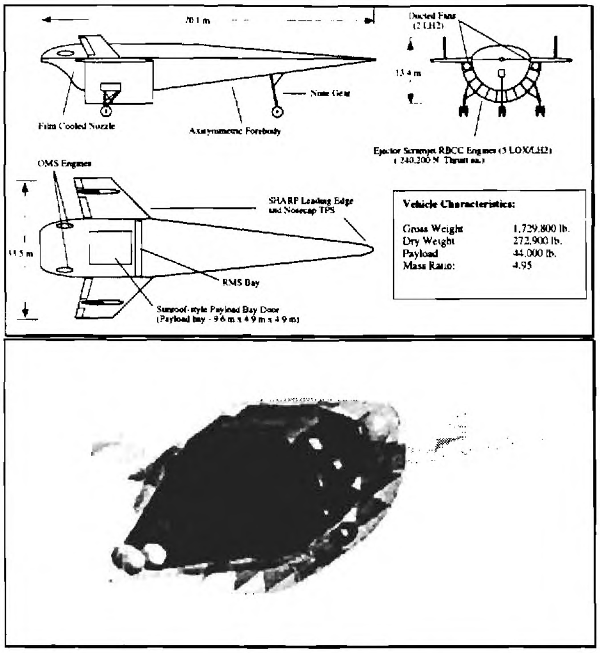


Figure 6: Hyperion Vehicle

The technology readiness level (TRL) for the Hyperion vehicle was much lower than the all rocket vehicle mainly because of the use of RBCC engines. This resulted in higher complexity factors for Hyperion compared to those used for the other vehicle. Since Hyperion utilizes a horizontal take-off, larger landing gear, wings, and tail were required. These factors resulted in an overall heavier dry weight for Hyperion.

6. RESULTS

The analysis was performed in three stages. In the first stage, only the weight parameters were evaluated by allowing the weights of the different component groups to vary while holding all other variables constant. In the second stage, only the market parameters were evaluated. In the final stage, the weight and market parameters were allowed to vary simultaneously during the simulation runs. The following three sections analyze the findings from the three stages.

6.1. Phase One Results

In phase one, a Monte Carlo simulation of 5000 trials was run for the Hyperion vehicle, during which only the weight variables were allowed to fluctuate. The results of this analysis show that certain component groups exert greater influence upon the financial performance of the overall program than do others. Figure 7 shows the sensitivity of the model toward the different component groups for Hyperion. In this case, the body group exhibits the highest correlation to the NPV of the program. The main propulsion system and the wing group also play a significant role in the determination of the economic performance of the vehicle.

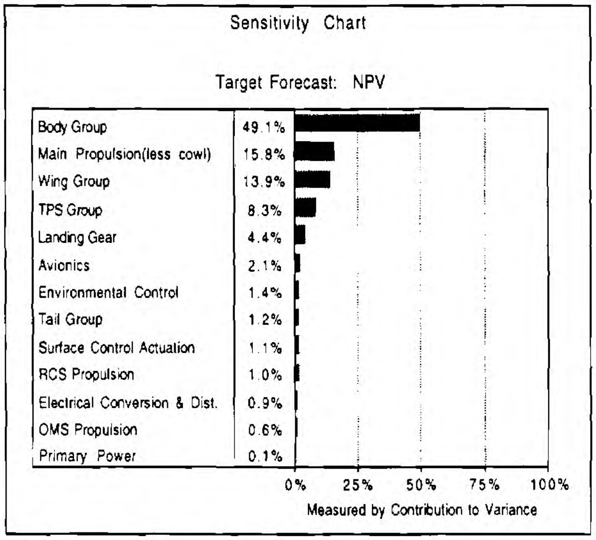


Figure 7: Sensitivity Chart for Hyperion

Figure 8 shows the frequency distribution for the IRR forecast value of Hyperion. The results display a double hump in the distribution implying that two values were equally likely to occur instead of just one, which occurs under a normal distribution. This result was explained by the methodology employed by CABAM in calculating revenue streams. For the passenger missions, a level of market demand was determined based upon the equations shown in the analysis section. This market demand was then divided by the payload capacity of the mission, resulting in a flight rate for the program.

Due to rounding, certain cases resulted in the same flight rate however at differing capacities, which translated into different revenue streams for the different cases.

For example, if the capacity of a launch was twenty passengers and the market demand was estimated to be forty-five passengers per year, then total passenger flights per year would be calculated as two. In the next trial, the number of passengers might decrease to eighteen due to weight growth. The number of passenger flights flown per year would remain at two, however the revenue would decrease by two passengers per flight. Over the total life of the program, this would result in a significant loss of revenue. Note the inherent assumption that partially full flights are not flown in the model.

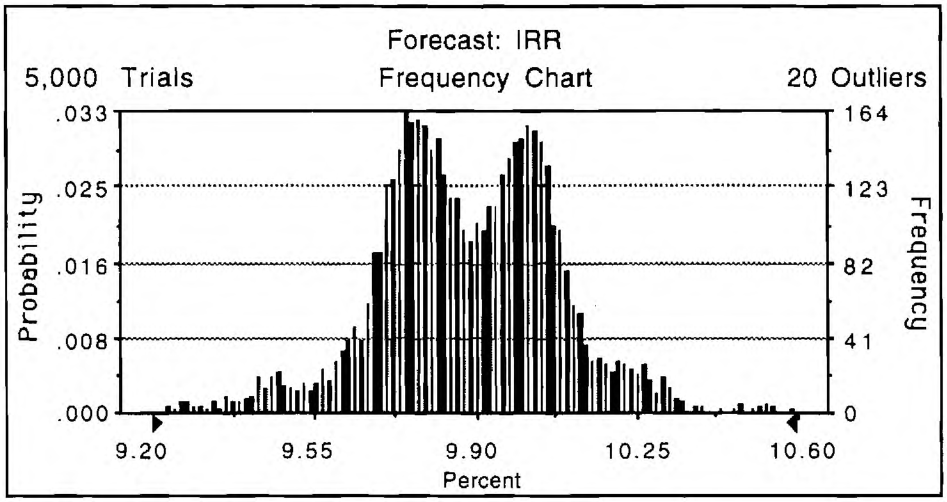


Figure 8: Stage One Frequency Distribution

6.2. Phase Two Results

In phase two, the market variables were allowed to vary while holding all other variables constant during the Monte Carlo simulation. The sensitivity analysis showed that the financial performance of the program was most sensitive to changes in the commercial cargo market. The government cargo market held a distant second, with the passenger missions holding positions three and four. The simulation resulted in a normal distribution for the IRR frequency distribution for the Hyperion vehicle as shown in Figure 9.

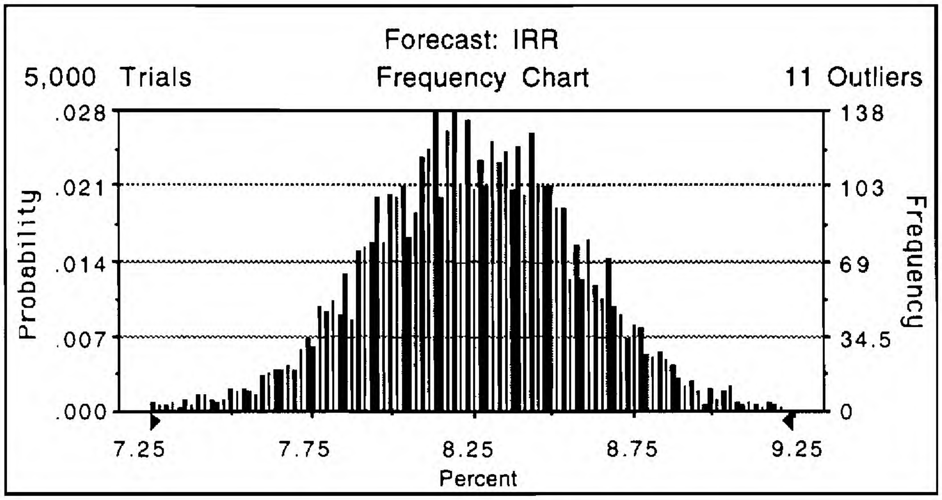


Figure 9: Stage Two Frequency Distribution

The results of the first two phases were compared to determine if one parameter significantly outweighed the other parameter in terms of volatility to the overall program. The mean value of the IRR for the first stage simulation run was 9.9%, with a standard deviation of 0.2. The mean value for the second stage run was 8.36% with a standard deviation of 0.3. As shown by the standard deviations, neither parameter swamped the other in terms of significance to the overall financial performance. The phase two simulation run resulted in a lower IRR compared to stage one because the dry weight margin was not added into payload capacity during the market parameter fluctuation run.

6.3. Phase Three Results

In the third phase, market and weight parameters were allowed to vary simultaneously for both vehicles during the Monte Carlo simulation runs. The results show that the model was more sensitive towards changes in the market parameters than to changes in the weights. As Figure 10 and Figure 11 show, the highest correlation existed between the economic indicators, in this case NPV, and the commercial cargo market.

These charts show that market volatility exerted greater influence over the financial outcome of the project compared to fluctuations in weight parameters. Specifically, changes in the demand for the commercial cargo market had the greatest impact upon the economic viability of an advanced space launch vehicle program under the parameters set forth in this analysis. This was a common result for both vehicles, however the results for weight parameters differ between Hyperion and the rocket vehicle.

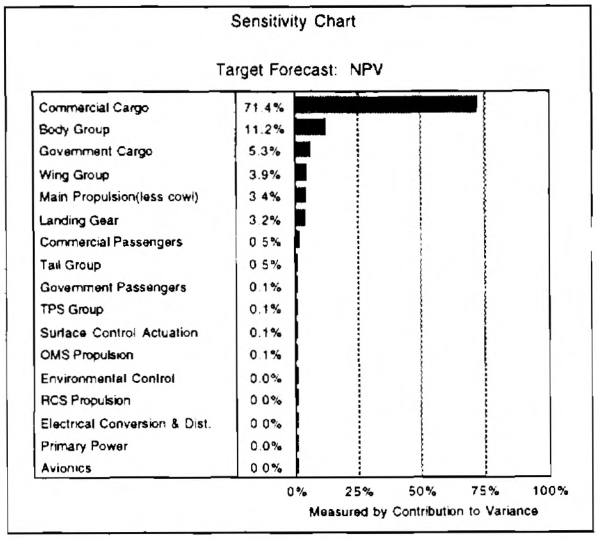


Figure 10: Sensitivity Chart for Hyperion

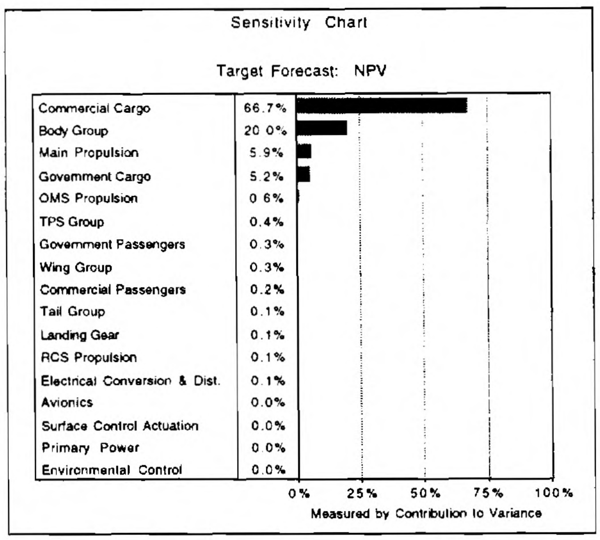


Figure 11: Sensitivity Chart for Rocket Vehicle

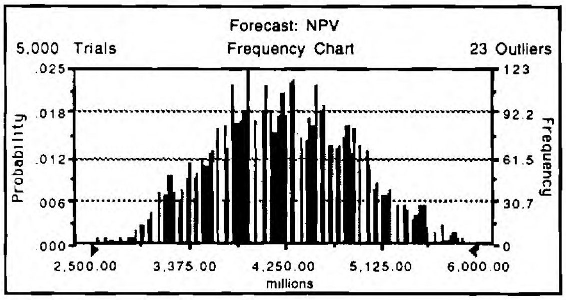
For the weight parameters, the results corresponded with the weight breakdowns for the vehicles in terms of significance. For Hyperion, the body, wings, landing gear, and main propulsion system were the most significant in terms of weight requirement. From this information, the economic validity of utilizing horizontal take-offs might be questioned due to the need for heavier components that result from this feature.

For the rocket vehicle, the body and the main propulsion system were the most significant. Therefore, designers could infer from these findings that changes in the weight of the body group and propulsion system would have a significant impact upon the financial outlook of the design. Conversely, improvements in the weights of avionics, surface control actuation, primary power, and environmental control would have minimal impact upon the profitability of the overall program. From this, it may be concluded that by improving the accuracy of the estimates of weight for the component groups that had the higher sensitivity values will minimize the overall economic risk associated with weight estimations.

The results for the two vehicles broken down by economic indicators, NPV and IRR, are shown in Figure 12. The charts depict the frequency distributions for each vehicle, with the corresponding statistics listed below each of the charts. The statistics highlight the important findings from each of the simulation runs.

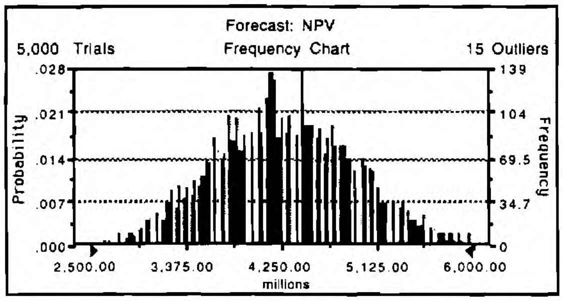
The NPV showed a variability of +-50% of the mean value for both vehicles. The rocket vehicle had a slightly higher average than Hyperion and a slightly lower standard deviation. Based upon these findings, the rocket vehicle would be a superior investment because of the higher return coupled with the lower risk value. However, the difference in return between these two vehicles was marginal. The simulation runs for the forecast value IRR resulted in the exact same standard deviation for both vehicles. As a percentage of the mean value, the standard deviation was approximately 6% for both simulations. These statistics show that by varying the weight and market parameters by the values defined previously results in significant volatility in the financial outcome of the project.

Hyperion

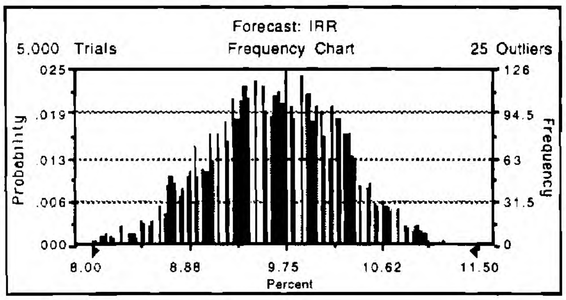


Statistics:	Value
Trials	5000
Mean	4,231.28
Median	4,220.15
Mode	- - -
Standard Deviation	653.06
Variance	426,488.36
Skewness	0.05
Kurtosis	2.74
Coeff. of Variability	0.15
Range Minimum	1,657.69
Range Maximum	6,279.83
Range Width	4,622.14
Mean Std. Error	9.24

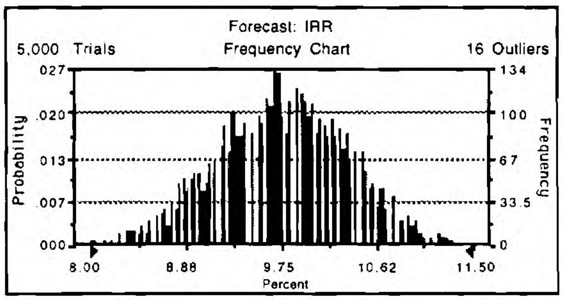
Rocket



Statistics:	Value
Trials	5000
Mean	4,282.63
Median	4,271.14
Mode	- - -
Standard Deviation	635.96
Variance	404,440.04
Skewness	0.06
Kurtosis	2.74
Coeff. of Variability	0.15
Range Minimum	2,123.13
Range Maximum	6,344.48
Range Width	4,221.35
Mean Std. Error	8.99



Statistics:	Value
Trials	5000
Mean	9.65
Median	9.67
Mode	- - -
Standard Deviation	0.61
Variance	0.37
Skewness	-0.17
Kurtosis	2.90
Coeff. of Variability	0.06
Range Minimum	6.85
Range Maximum	11.38
Range Width	4.53
Mean Std. Error	0.01



Statistics:	Value
Trials	5000
Mean	9.75
Median	9.76
Mode	- - -
Standard Deviation	0.61
Variance	0.38
Skewness	-0.17
Kurtosis	2.84
Coeff. of Variability	0.06
Range Minimum	7.39
Range Maximum	11.51
Range Width	4.12
Mean Std. Error	0.01

Figure 12: Comparison of Results for Both Vehicles

6.4. Reward-to-Variability Ratio

In performing a financial analysis of a project, it is imperative that the reward be taken in context with the amount of risk assumed. The Sharpe ratio is an economic indicator that combines both factors into a single metric. Introduced in 1966 by Professor William Sharpe of Stanford University, the Sharpe ratio was intended to measure the performance of mutual funds. It has gained considerable popularity in the financial community as a metric for comparing different investments. As shown in equation 4, to arrive at the Sharpe ratio, the risk-free rate, r_{rf}, is subtracted from the average return of the project, which is then divided by the standard deviation of the return, $\sigma(x)$.[9]

$$SR(x) = \frac{\bar{r}(x) - r_{rf}}{\sigma(x)} \qquad (4)$$

For illustration purposes, the Sharpe ratio of a portfolio held from 1954 to 1994 containing shares from all stocks with a market capitalization over $150 million was 43.[10] From the analysis, the Sharpe ratio was calculated for Hyperion as 7.2 and for the SSTO all rocket vehicle as 7.3 using a risk-free rate of 5.27% as shown in Table 3.[11] The risk free rate was derived from the current yield on 30-year government bonds. In terms of the Sharpe ratio, higher numbers indicate better risk-adjusted returns.

Table 3: Values Used in Sharpe Calculation

	r_{rf}	$\bar{r}(x)$	σ	SR(x)
Hyperion	5.27%	9.65%	0.61%	7.2
Rocket	5.27%	9.75%	0.61%	7.3

The 30-year government bond yield was chosen because it contains no default risk and matches the term in years of the launch vehicle program. It might be argued that a shorter-term government security would eliminate interest rate risk, which should not be included in the calculation of the Sharpe ratio for this type of analysis. However, short-term government securities do not reflect expected long run changes in inflation. Therefore, there is a trade-off in using either rate, but the overall implications to the value obtained from the Sharpe ratio calculation are marginal.

In this analysis, the results of using the Sharpe ratio only quantify the risk associated with market volatility and variances in the weight parameters of the different components. Many other factors create risk in this type of project that might adversely or positively affect the financial viability for an advanced space launch program. Therefore, the identification of the Sharpe ratio obtained by a stock portfolio in a previous paragraph was not meant as a comparison to the results obtained from the two vehicles, but rather to provide an illustration of the numeric values expected.

7. DISCUSSION

In the analysis section, the Sharpe ratio was introduced as a metric that might be used for the financial analysis of advanced space launch vehicle programs during the conceptual design phase. This ratio was originally developed for the sole purpose of evaluating mutual funds based upon past performance. Experts in the field might question the validity of using this ratio for the purposes outlined in this paper. It has been suggested that derivatives of the equation might be preferable for this type of evaluation.

A possible alternative for equation 4 would be to eliminate the use of the risk free rate, thereby dividing the average return by the standard deviation. This would result in values of approximately 16 for the two vehicles analyzed in this paper. It has also been suggested that average return should be divided by the standard deviation squared. This would raise the value to approximately 26 for Hyperion and the rocket vehicle. These two derivative equations would simplify the process for the conceptual designer as well as eliminate the controversy associated with determining an appropriate value for the risk free rate.

If the relationship between the total economic risk of the project and the risk associated with these two factors was known, then a scale factor could be applied to the ratio. This would provide a result that could be used in a comparative environment with other launch programs as well as other investment projects.

8. CONCLUSIONS

The goal of this research was to investigate the effects of uncertainties associated with weight and market parameters in determining the economic viability of advanced space launch vehicles. Market sensitivity and weight-based cost estimating relationships are key drivers in determining the financial viability of a project. The expected uncertainty associated with these two factors drives the economic risk of the overall program. Monte Carlo simulation techniques were incorporated into the analysis to determine the sensitivity of the model to changes in market and weight parameters. From this, the risk generated by the variability of these two parameters was quantified.

From the findings of the Monte Carlo simulations, it may be concluded that the volatility of the market will play an integral role in the viability of commercial advanced space flight vehicle programs. These findings emphasize the importance of the need for accurate market demand forecasts. For weight parameters, the results suggest that certain component groups, depending on the vehicle type, dominate others in terms of significance to the overall economic viability of a launch program. From this, it may be concluded that improving the accuracy of the estimates of weight for certain component groups will minimize the overall economic risk associated with weight estimations.

In addition to these findings, a metric was introduced which would quantify the risk as it relates to the return of the project. This provides designers with a basis from which to work in identifying the value of different factors that may affect the financial outcome of an advanced space flight program. In terms of weight estimations, by improving the confidence level of the predictions made about the weights of specific components, the Sharpe ratio may be increased for the whole program, thereby improving the financial viability of the design by lowering the amount of risk incurred. Utilizing CABAM and Crystal Ball, further investigations may be made into other factors that create uncertainty in the financial outlook of space launch vehicles.

From the analysis, it was determined that the all rocket vehicle was a better investment due to the higher Sharpe ratio. In terms of IRR, both vehicles displayed the same risk value for weight and market parameters as a whole, however the rocket vehicle had a slightly higher return. Since the analysis was performed at a conceptual design stage, the difference in the financial viability was marginal and should not be a determinant in choosing between the two vehicles at this stage of development. It should also be noted that the analysis was performed based upon subjective assessments of weight variability and market volatility.

9. FUTURE WORK

Future work for this research may include the investigation of other factors that might affect the economic viability of a launch program. This would include not only items directly related to the design of a vehicle, but also economic factors and government incentive programs that could have far reaching implications for the advancement of space flight.

Other possible areas of interest for this type of investigation might include the analysis of targeted marketing efforts. Certain areas of the market may provide a higher level of stability for commercial launch service providers, but at what cost to return? For example, if a launch service concentrated solely on the government passenger market, the risk would be significantly reduced, however the return might be considerably lower, thus resulting in an overall lower quality project in terms of financial viability.

An expansion upon the use of the Sharpe ratio in determining the economic performance of advanced space launch vehicle programs might be another area of consideration for investigation. The intention here would be to try to incorporate and quantify the total risk of the program, thereby providing a metric for use in the comparison of alternative launch programs.

CABAM will continue to be improved by expanding upon the modules within the model and by adding new components to the overall structure.

10. ACKNOWLEDGEMENTS

The author would like to thank Dr. Olds for his patience and understanding attitude, as well as his support in completing this work. The author would also like to thank the members of the Georgia Institute of Technology Space Systems Design Laboratory for their support. John Bradford, Laura Ledsinger, David McCormick, Jeff Scott, and Jeff Whitfield generated design data and graphics for the vehicle "Hyperion". David Way, John Bradford, Laura Ledsinger, David McCormick, Jeff Scott, and Jeff Whitfield generated design data and graphics for the SSTO rocket vehicle.

The author would also like to thank Eric Shaw of NASA's Marshall Space Flight Center (MSFC) for his support in providing insight into the economics of RLVs and methodologies used for business simulation analysis.

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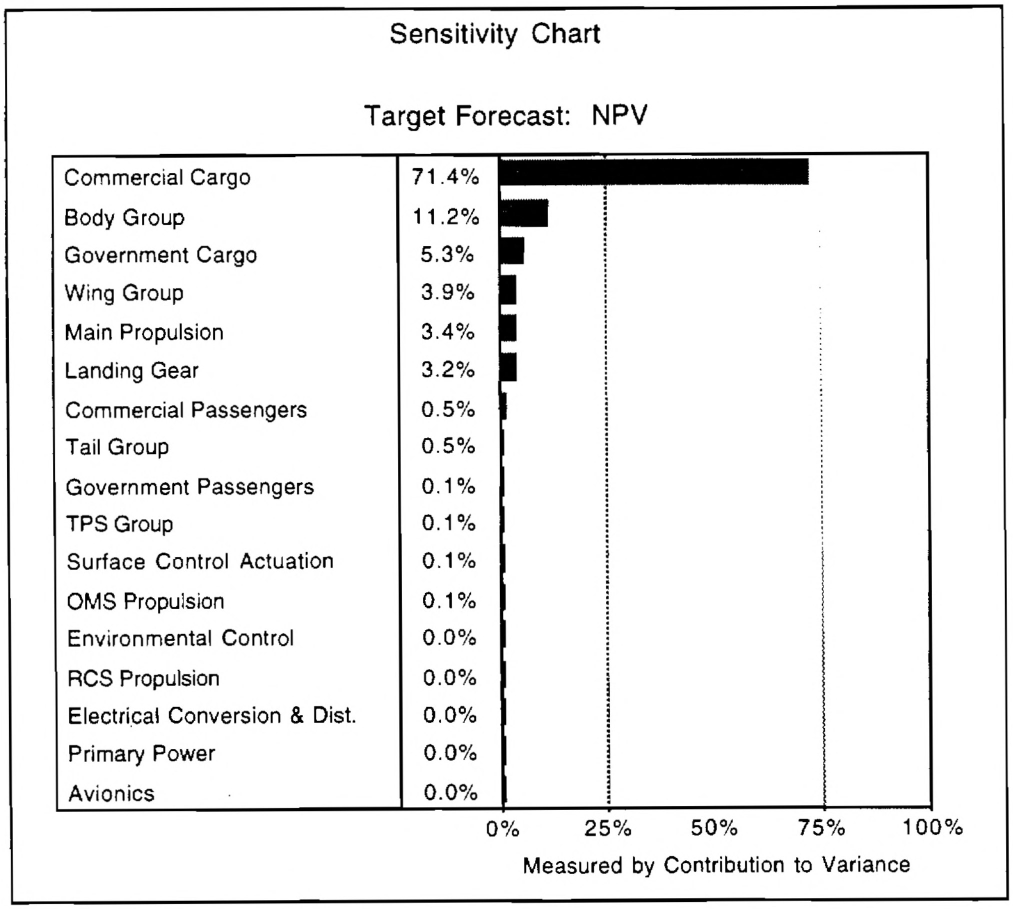
12. Phase Three Output for Hyperion Simulation Run

12.1. Sensitivity Chart

Crystal Ball Report
Simulation started on Fri, Sep 18, 1998 at 4:46:20 PM
Simulation stopped on Fri, Sep 18, 1998 at 10:42:32 PM

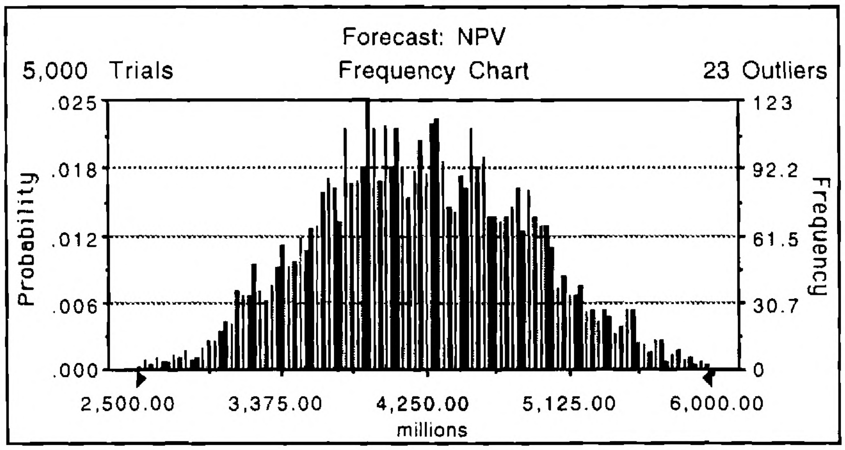


12.2. Forecast Results for NPV

Forecast: NPV **Cell: B31**

Summary:
Display Range is from 2,500.00 to 6,000.00 millions
Entire Range is from 1,657.69 to 6,279.83 millions
After 5,000 Trials, the Std. Error of the Mean is 9.24

Statistics:	Value
Trials	5000
Mean	4,231.28
Median	4,220.15
Mode	---
Standard Deviation	653.06
Variance	426,488.36
Skewness	0.05
Kurtosis	2.74
Coeff. of Variability	0.15
Range Minimum	1,657.69
Range Maximum	6,279.83
Range Width	4,622.14
Mean Std. Error	9.24

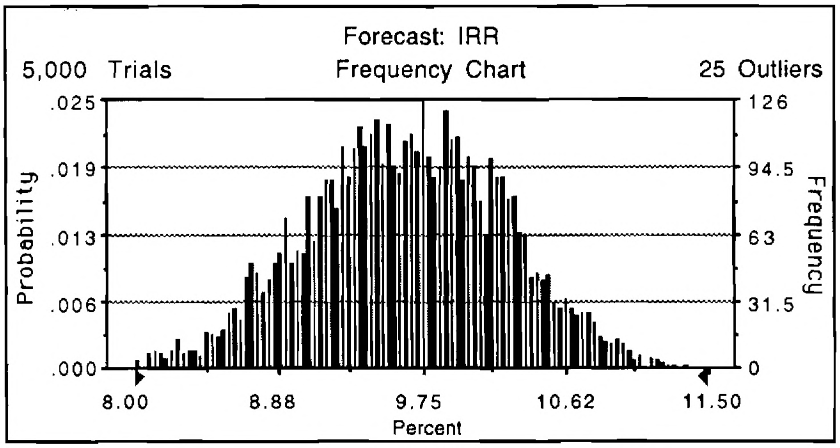


12.3. *Forecast Results for IRR*

Forecast: IRR **Cell: B32**

Summary:
Display Range is from 8.00 to 11.50 Percent
Entire Range is from 6.85 to 11.38 Percent
After 5,000 Trials, the Std. Error of the Mean is 0.01

Statistics:	Value
Trials	5000
Mean	9.65
Median	9.67
Mode	- - -
Standard Deviation	0.61
Variance	0.37
Skewness	-0.17
Kurtosis	2.90
Coeff. of Variability	0.06
Range Minimum	6.85
Range Maximum	11.38
Range Width	4.53
Mean Std. Error	0.01



12.4. Assumptions

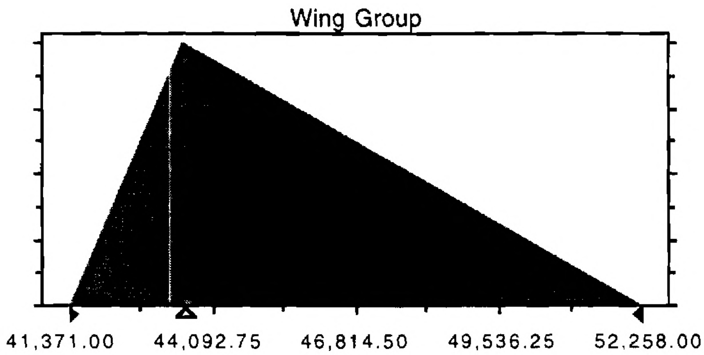
12.4.1.Weight Variables

Assumption: Wing Group **Cell: B12**

Triangular distribution with parameters:

Minimum	41,371.00
Likeliest	43,548.00
Maximum	52,258.00

Selected range is from 41,371.00 to 52,258.00
Mean value in simulation was 45,731.43

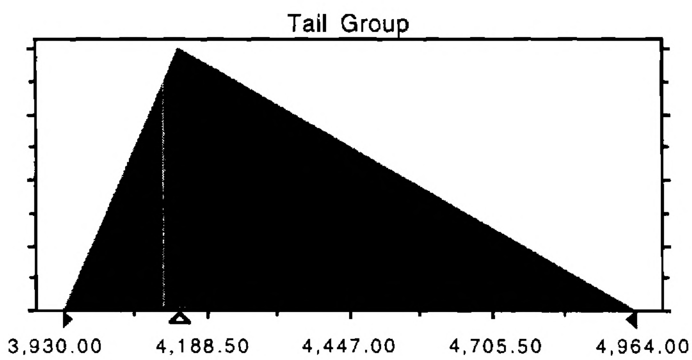


Assumption: Tail Group **Cell: B13**

Triangular distribution with parameters:

Minimum	3,930.00
Likeliest	4,137.00
Maximum	4,964.00

Selected range is from 3,930.00 to 4,964.00
Mean value in simulation was 4,345.42

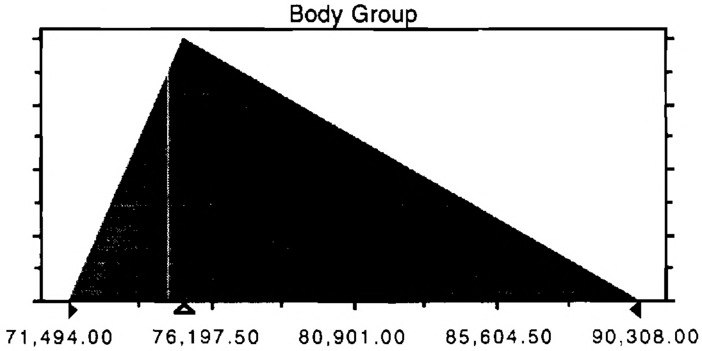


Assumption: Body Group **Cell: B14**

Triangular distribution with parameters:

Minimum	71,494.00
Likeliest	75,257.00
Maximum	90,308.00

Selected range is from 71,494.00 to 90,308.00
Mean value in simulation was 79,032.87

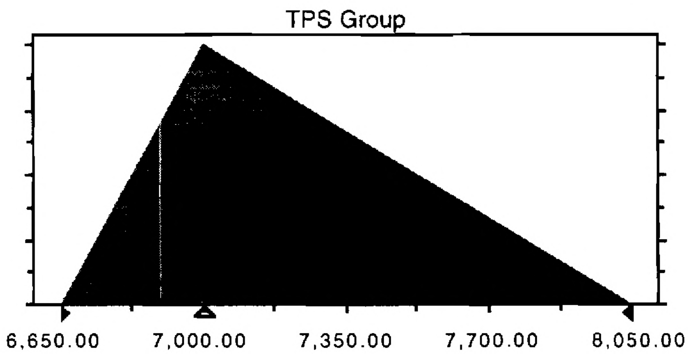


Assumption: TPS Group **Cell: B15**

Triangular distribution with parameters:

Minimum	6,650.00
Likeliest	7,000.00
Maximum	8,050.00

Selected range is from 6,650.00 to 8,050.00
Mean value in simulation was 7,233.54

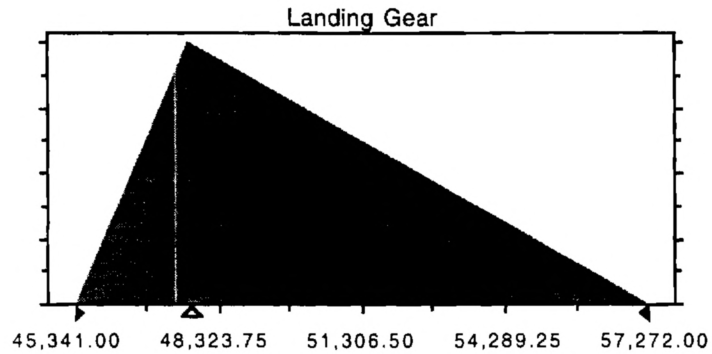


Assumption: Landing Gear **Cell: B16**

Triangular distribution with parameters:

Minimum	45,341.00
Likeliest	47,727.00
Maximum	57,272.00

Selected range is from 45,341.00 to 57,272.00
Mean value in simulation was 50,146.65

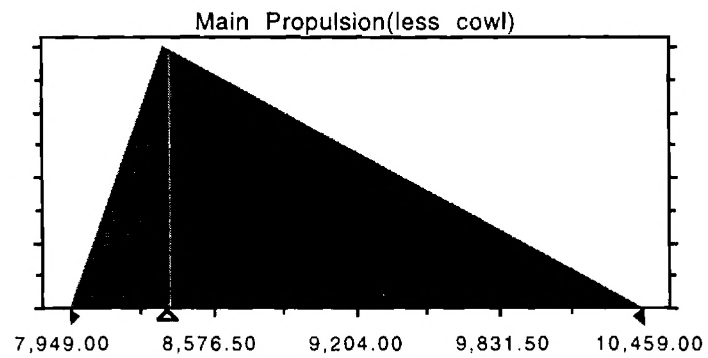


Assumption: Main Propulsion(less cowl) **Cell: B17**

Triangular distribution with parameters:

Minimum	7,949.00
Likeliest	8,367.00
Maximum	10,459.00

Selected range is from 7,949.00 to 10,459.00
Mean value in simulation was 8,918.02

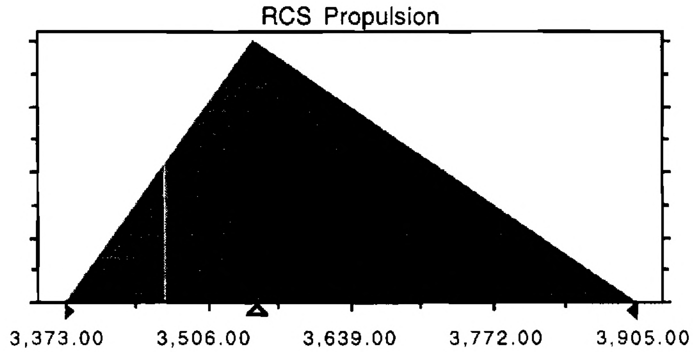


Assumption: RCS Propulsion **Cell: B18**

Triangular distribution with parameters:

Minimum	3,373.00
Likeliest	3,550.00
Maximum	3,905.00

Selected range is from 3,373.00 to 3,905.00
Mean value in simulation was 3,608.15

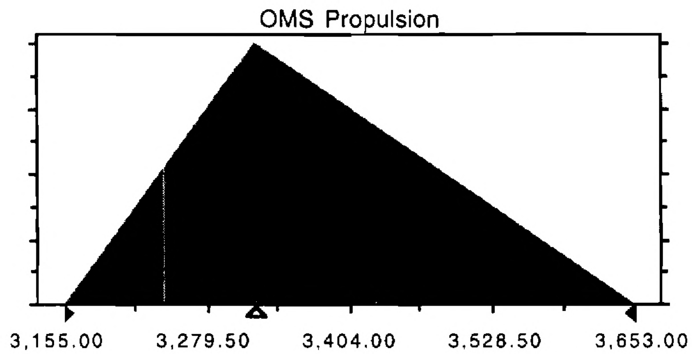


Assumption: OMS Propulsion **Cell: B19**

Triangular distribution with parameters:

Minimum	3,155.00
Likeliest	3,321.00
Maximum	3,653.00

Selected range is from 3,155.00 to 3,653.00
Mean value in simulation was 3,377.95

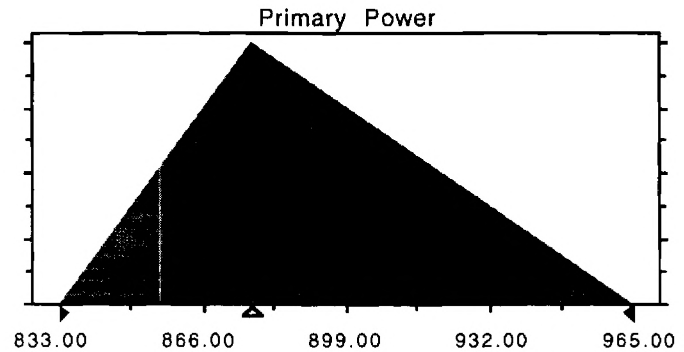


Assumption: Primary Power **Cell: B20**

Triangular distribution with parameters:

Minimum	833.00
Likeliest	877.00
Maximum	965.00

Selected range is from 833.00 to 965.00
Mean value in simulation was 891.90

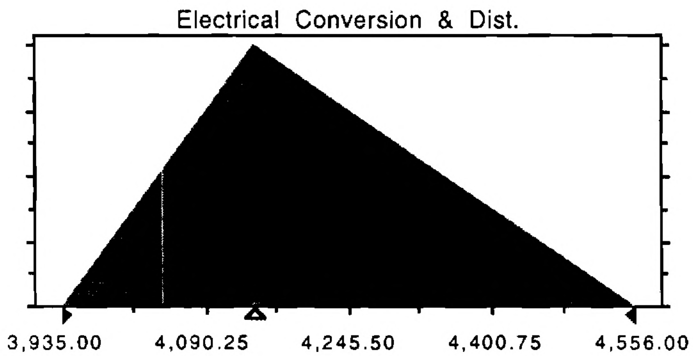


Assumption: Electrical Conversion & Dist. **Cell: B21**

Triangular distribution with parameters:

Minimum	3,935.00
Likeliest	4,142.00
Maximum	4,556.00

Selected range is from 3,935.00 to 4,556.00
Mean value in simulation was 4,207.85

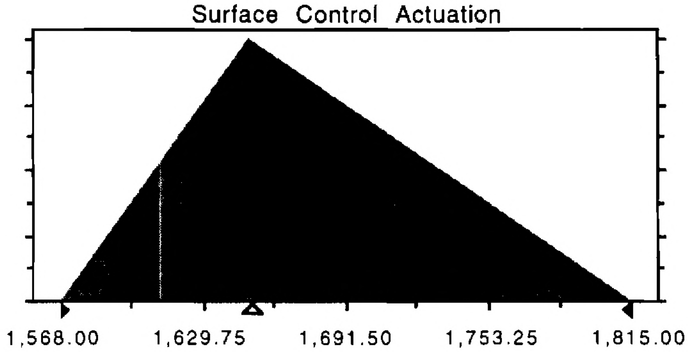


Assumption: Surface Control Actuation **Cell: B23**

Triangular distribution with parameters:

Minimum	1,568.00
Likeliest	1,650.00
Maximum	1,815.00

Selected range is from 1,568.00 to 1,815.00
Mean value in simulation was 1,677.38

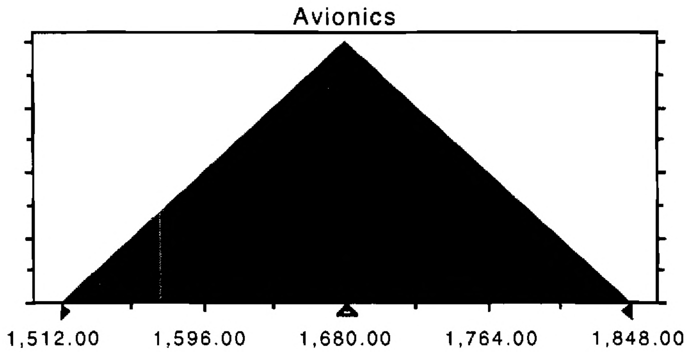


Assumption: Avionics **Cell: B24**

Triangular distribution with parameters:

Minimum	1,512.00
Likeliest	1,680.00
Maximum	1,848.00

Selected range is from 1,512.00 to 1,848.00
Mean value in simulation was 1,681.02

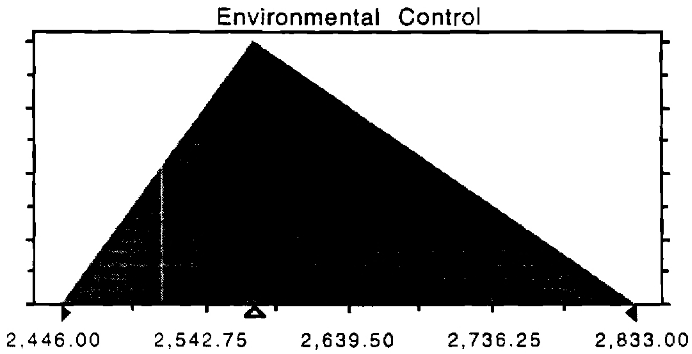


Assumption: Environmental Control **Cell: B25**

Triangular distribution with parameters:

Minimum	2,446.00
Likeliest	2,575.00
Maximum	2,833.00

Selected range is from 2,446.00 to 2,833.00
Mean value in simulation was 2,618.24



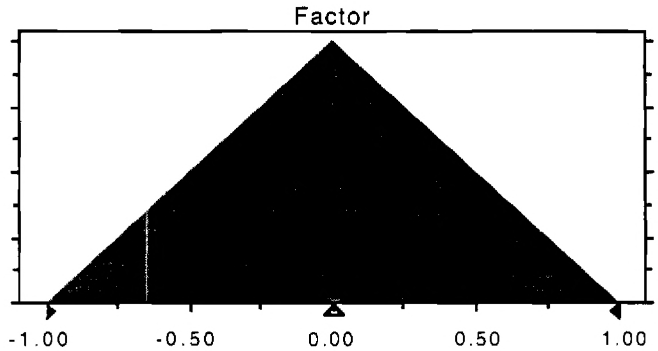
12.4.2.Market Variables

Assumption: Commercial Cargo **Cell: B4**

Triangular distribution with parameters:

Minimum	-1.00
Likeliest	0.00
Maximum	1.00

Selected range is from -1.00 to 1.00
Mean value in simulation was 0.00

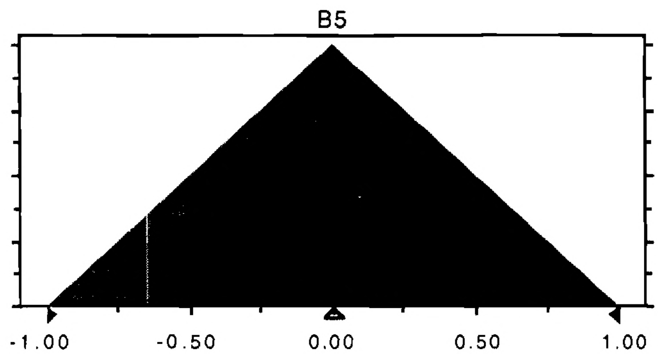


Assumption: Commercial Passengers **Cell: B5**

Triangular distribution with parameters:

Minimum	-1.00
Likeliest	0.00
Maximum	1.00

Selected range is from -1.00 to 1.00
Mean value in simulation was 0.00

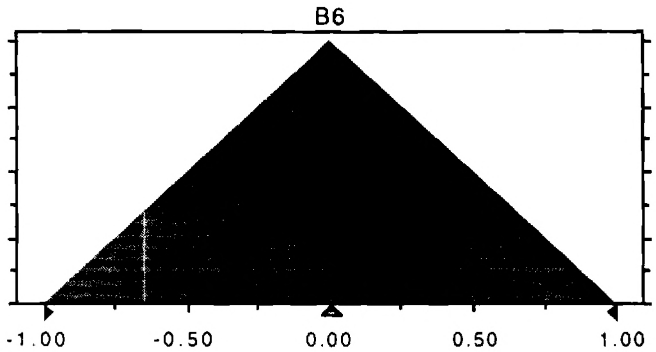


Assumption: Government Cargo **Cell: B6**

Triangular distribution with parameters:

Minimum	-1.00
Likeliest	0.00
Maximum	1.00

Selected range is from -1.00 to 1.00
Mean value in simulation was 0.00

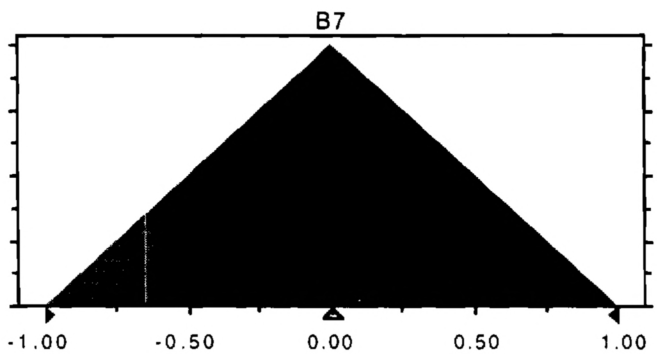


Assumption: Government Passengers **Cell: B7**

Triangular distribution with parameters:

Minimum	-1.00
Likeliest	0.00
Maximum	1.00

Selected range is from -1.00 to 1.00
Mean value in simulation was 0.00



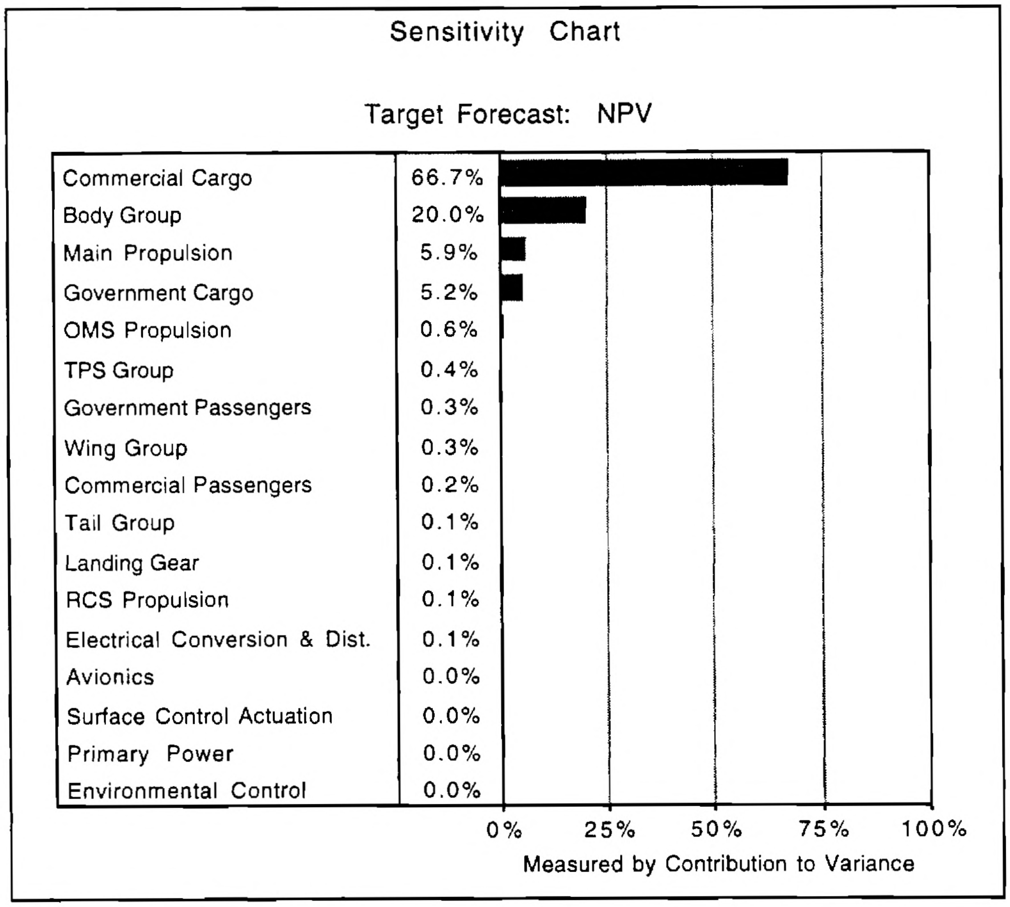
End of Assumptions

13. Phase Three Output for Rocket Vehicle Simulation Run

13.1. Sensitivity Chart

Crystal Ball Report

Simulation started on Sat, Sep 19, 1998 at 11:43:05 AM
Simulation stopped on Sat, Sep 19, 1998 at 5:48:47 PM

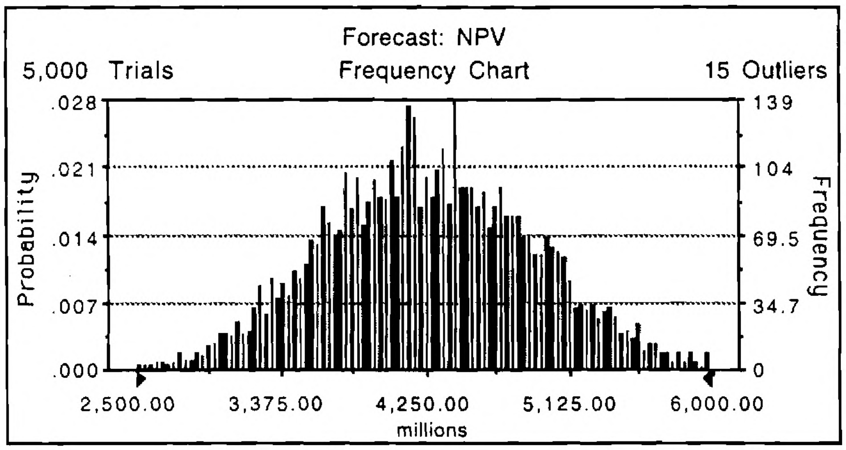


13.2. *Forecast Results for NPV*

Forecast: NPV **Cell: B31**

Summary:
Display Range is from 2,500.00 to 6,000.00 millions
Entire Range is from 2,123.13 to 6,344.48 millions
After 5,000 Trials, the Std. Error of the Mean is 8.99

Statistics:	Value
Trials	5000
Mean	4,282.63
Median	4,271.14
Mode	- - -
Standard Deviation	635.96
Variance	404,440.04
Skewness	0.06
Kurtosis	2.74
Coeff. of Variability	0.15
Range Minimum	2,123.13
Range Maximum	6,344.48
Range Width	4,221.35
Mean Std. Error	8.99

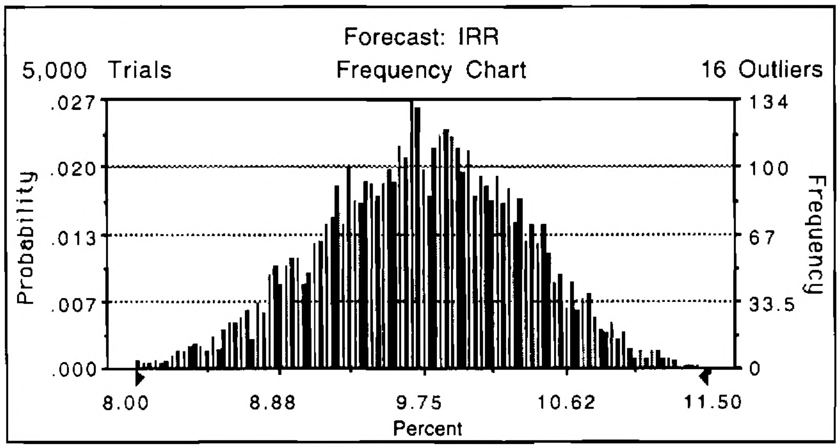


13.3. *Forecast Results for IRR*

Forecast: IRR **Cell: B32**

Summary:
Display Range is from 8.00 to 11.50 Percent
Entire Range is from 7.39 to 11.51 Percent
After 5,000 Trials, the Std. Error of the Mean is 0.01

Statistics:	Value
Trials	5000
Mean	9.75
Median	9.76
Mode	- - -
Standard Deviation	0.61
Variance	0.38
Skewness	-0.17
Kurtosis	2.84
Coeff. of Variability	0.06
Range Minimum	7.39
Range Maximum	11.51
Range Width	4.12
Mean Std. Error	0.01



13.4. Assumptions

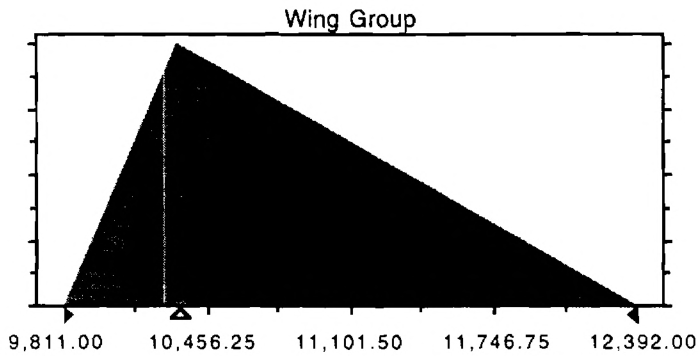
13.4.1.Weight Variables

Assumption: Wing Group **Cell: B12**

Triangular distribution with parameters:

Minimum	9,811.00
Likeliest	10,327.00
Maximum	12,392.00

Selected range is from 9,811.00 to 12,392.00
Mean value in simulation was 10,841.30

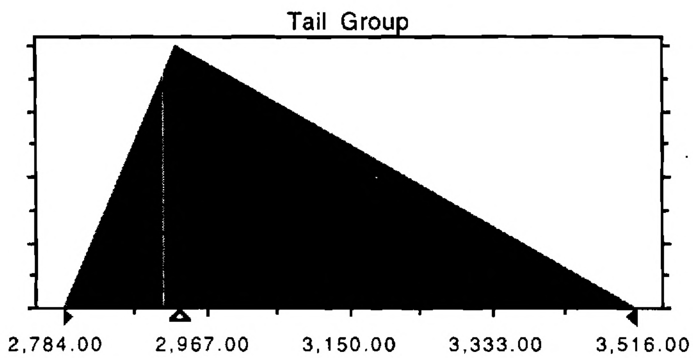


Assumption: Tail Group **Cell: B13**

Triangular distribution with parameters:

Minimum	2,784.00
Likeliest	2,930.00
Maximum	3,516.00

Selected range is from 2,784.00 to 3,516.00
Mean value in simulation was 3,077.37

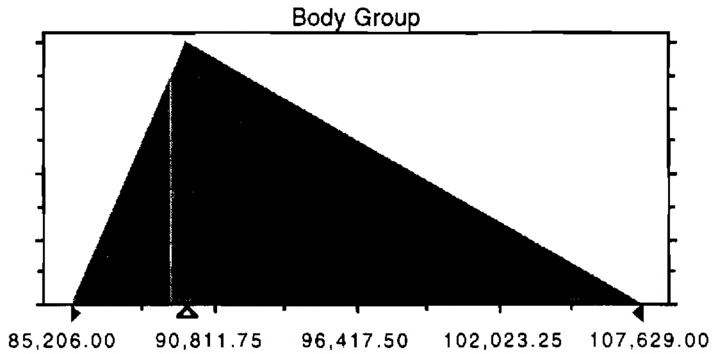


Assumption: Body Group **Cell: B14**

Triangular distribution with parameters:

Minimum	85,206.00
Likeliest	89,691.00
Maximum	107,629.00

Selected range is from 85,206.00 to 107,629.00
Mean value in simulation was 94,261.10

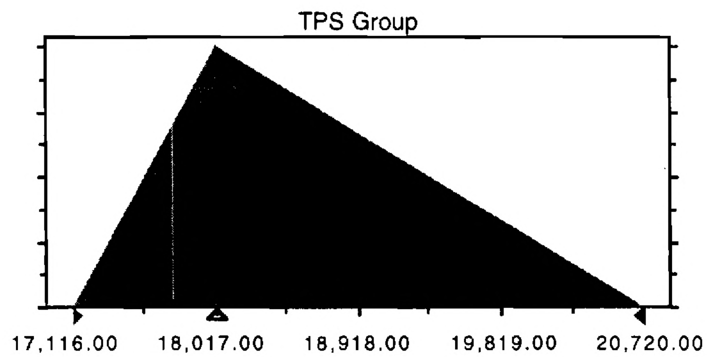


Assumption: TPS Group **Cell: B15**

Triangular distribution with parameters:

Minimum	17,116.00
Likeliest	18,017.00
Maximum	20,720.00

Selected range is from 17,116.00 to 20,720.00
Mean value in simulation was 18,632.94

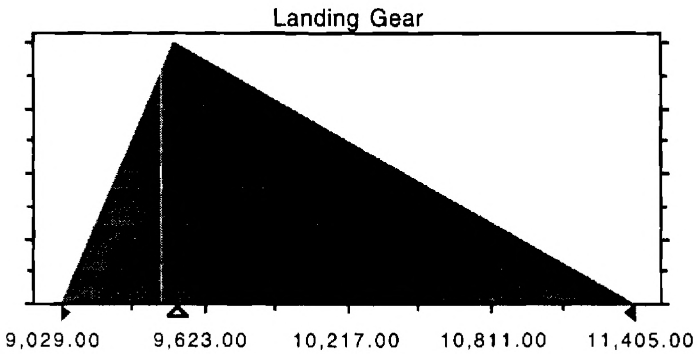


Assumption: Landing Gear **Cell: B16**

Triangular distribution with parameters:

Minimum	9,029.00
Likeliest	9,504.00
Maximum	11,405.00

Selected range is from 9,029.00 to 11,405.00
Mean value in simulation was 9,979.37

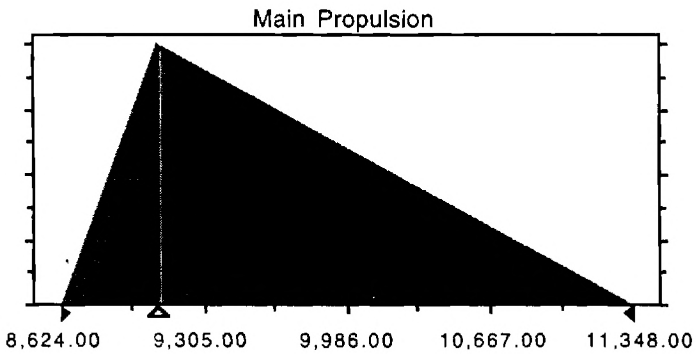


Assumption: Main Propulsion **Cell: B17**

Triangular distribution with parameters:

Minimum	8,624.00
Likeliest	9,078.00
Maximum	11,348.00

Selected range is from 8,624.00 to 11,348.00
Mean value in simulation was 9,681.84

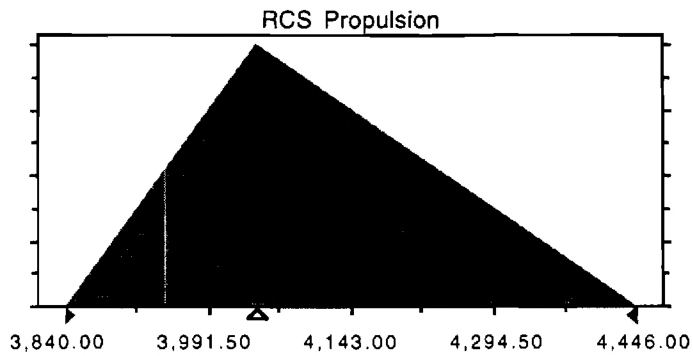


Assumption: RCS Propulsion **Cell: B18**

Triangular distribution with parameters:

Minimum	3,840.00
Likeliest	4,042.00
Maximum	4,446.00

Selected range is from 3,840.00 to 4,446.00
Mean value in simulation was 4,107.73

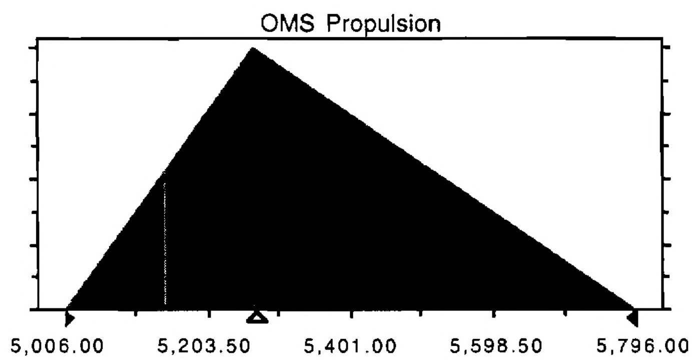


Assumption: OMS Propulsion **Cell: B19**

Triangular distribution with parameters:

Minimum	5,006.00
Likeliest	5,269.00
Maximum	5,796.00

Selected range is from 5,006.00 to 5,796.00
Mean value in simulation was 5,355.17

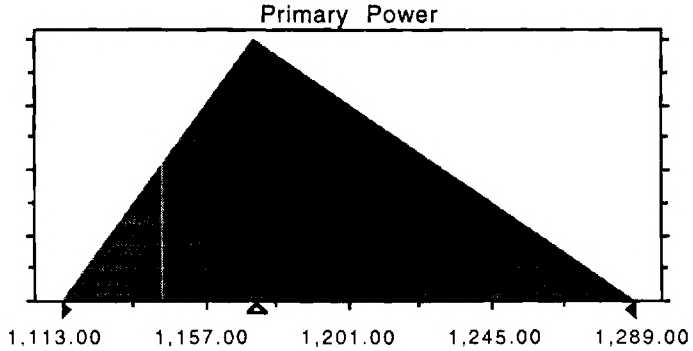


Assumption: Primary Power **Cell: B20**

Triangular distribution with parameters:

Minimum	1,113.00
Likeliest	1,172.00
Maximum	1,289.00

Selected range is from 1,113.00 to 1,289.00
Mean value in simulation was 1,191.76

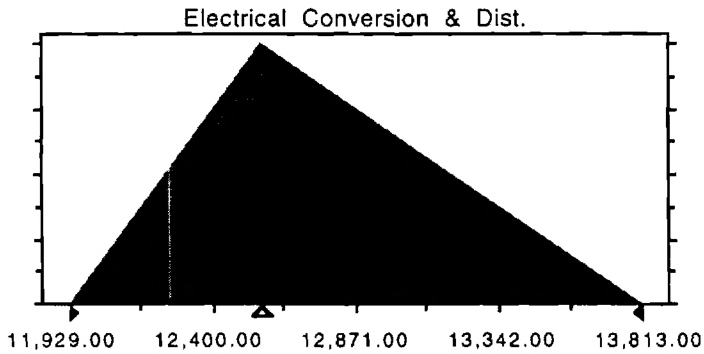


Assumption: Electrical Conversion & Dist. **Cell: B21**

Triangular distribution with parameters:

Minimum	11,929.00
Likeliest	12,557.00
Maximum	13,813.00

Selected range is from 11,929.00 to 13,813.00
Mean value in simulation was 12,760.28

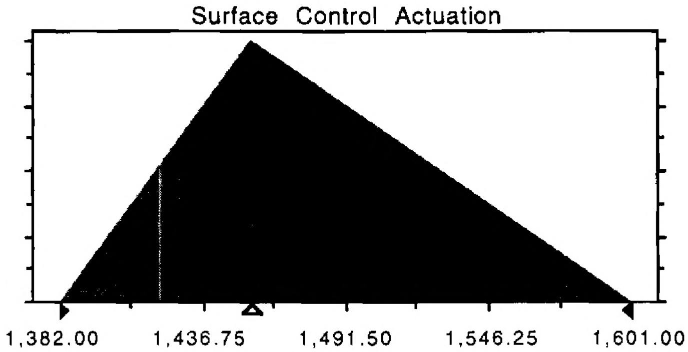


Assumption: Surface Control Actuation **Cell: B23**

Triangular distribution with parameters:

Minimum	1,382.00
Likeliest	1,455.00
Maximum	1,601.00

Selected range is from 1,382.00 to 1,601.00
Mean value in simulation was 1,480.06

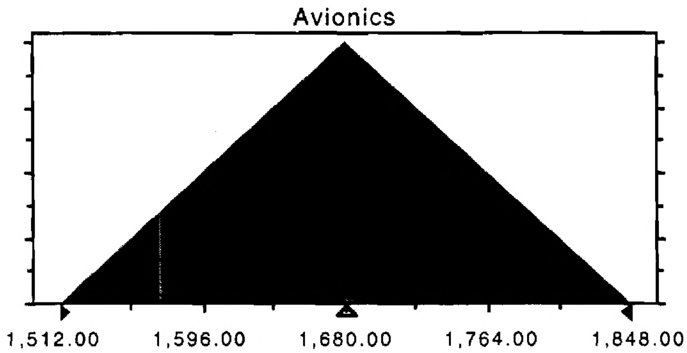


Assumption: Avionics **Cell: B24**

Triangular distribution with parameters:

Minimum	1,512.00
Likeliest	1,680.00
Maximum	1,848.00

Selected range is from 1,512.00 to 1,848.00
Mean value in simulation was 1,681.00

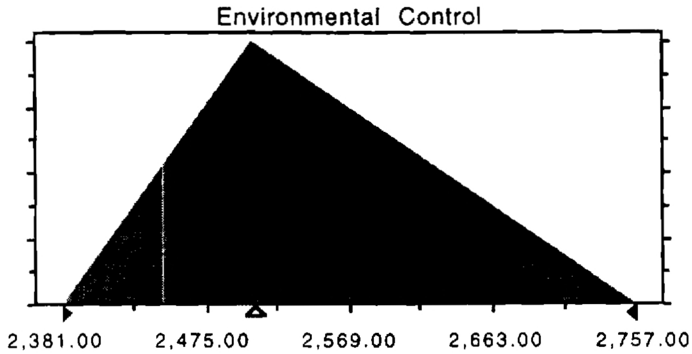


Assumption: Environmental Control **Cell: B25**

Triangular distribution with parameters:

Minimum	2,381.00
Likeliest	2,506.00
Maximum	2,757.00

Selected range is from 2,381.00 to 2,757.00
Mean value in simulation was 2,548.05



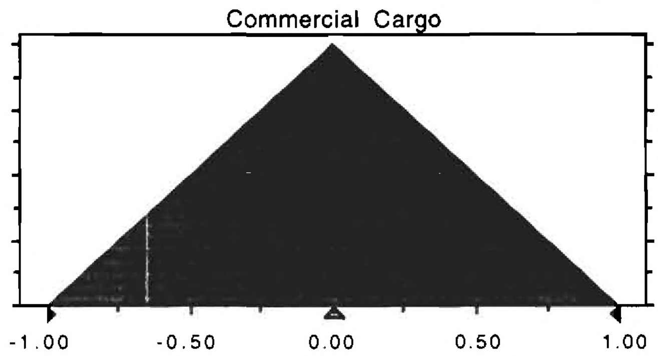
13.4.2.Market Variables

Assumption: Commercial Cargo **Cell: B4**

Triangular distribution with parameters:

Minimum	-1.00
Likeliest	0.00
Maximum	1.00

Selected range is from -1.00 to 1.00
Mean value in simulation was 0.00

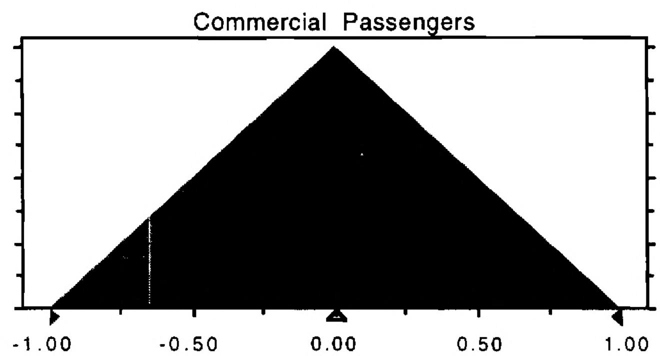


Assumption: Commercial Passengers **Cell: B5**

Triangular distribution with parameters:

Minimum	-1.00
Likeliest	0.00
Maximum	1.00

Selected range is from -1.00 to 1.00
Mean value in simulation was 0.00

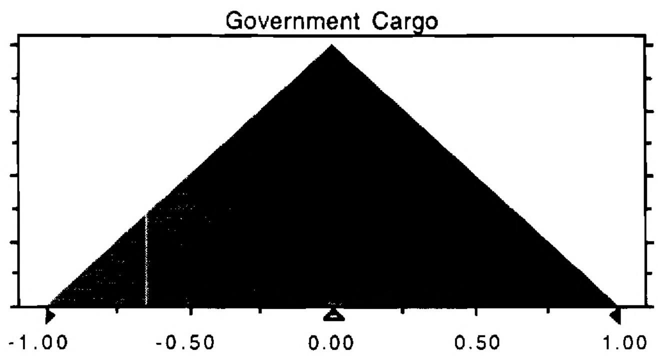


Assumption: Government Cargo **Cell: B6**

Triangular distribution with parameters:

Minimum	-1.00
Likeliest	0.00
Maximum	1.00

Selected range is from -1.00 to 1.00
Mean value in simulation was -0.00

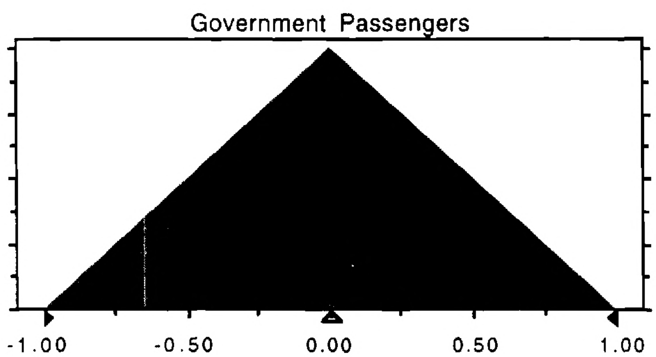


Assumption: Government Passengers **Cell: B7**

Triangular distribution with parameters:

Minimum	-1.00
Likeliest	0.00
Maximum	1.00

Selected range is from -1.00 to 1.00
Mean value in simulation was 0.01



End of Assumptions

AIAA 98-5179

Economic Uncertainty of Weight and Market Parameters for Advanced Space Launch Vehicles

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1998 Defense and Civil Space Programs Conference and Exhibit

Oct. 28-30, 1998 / Huntsville, AL

Economic Uncertainty of Weight and Market Parameters for Advanced Space Launch Vehicles

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ABSTRACT

Market sensitivity and weight-based cost estimating relationships are key drivers in determining the financial viability of advanced space launch vehicle designs. Due to decreasing space transportation budgets and increasing foreign competition, it has become essential for financial assessments of prospective launch vehicles to be performed during the conceptual design phase. As part of this financial assessment, it is imperative to understand the relationship between market volatility, the uncertainty of weight estimates, and the economic viability of an advanced space launch vehicle program.

This paper reports the results of a study that evaluated the economic risk inherent in market variability and the uncertainty of developing weight estimates for an advanced space launch vehicle program. The purpose of this study was to determine the sensitivity of a business case for advanced space flight design with respect to the changing nature of market conditions and the complexity of determining accurate weight estimations during the conceptual design phase. The expected uncertainty associated with these two factors drives the economic risk of the overall program.

The study incorporates Monte Carlo simulation techniques to determine the probability of attaining specific levels of economic performance when the market and weight parameters are allowed to vary. This structured approach toward uncertainties allows for the assessment of risks associated with a launch vehicle program's economic performance. This results in the determination of the value of the additional risk placed on the project by these two factors.

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† - *Assistant Professor, School of Aerospace Engineering, Senior member AIAA.*

NOMENCLATURE

CABAM	Cost and Business Analysis Module
CER	cost estimating relationship
CSTS	Commercial Space Transportation Study
DDT&E	design, development, test, & evaluation
EBIT	earnings before interest and taxes
ESJ	ejector scramjet
HTHL	horizontal take-off, horizontal landing
IOC	initial operating capability
IRR	internal rate of return
KSC	NASA Kennedy Space Center
LCC	life cycle cost
LEO	low earth orbit
LH2	liquid hydrogen
LOX	liquid oxygen
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Admin.
NASCOM	NASA Cost Model
NPV	net present value
RBCC	rocket-based combined cycle
RLV	reusable launch vehicle
ROI	return on investment
SSDL	Space Systems Design Laboratory
SSTO	single-stage to orbit
TFU	theoretical first unit
TRL	technology readiness level
VTHL	vertical take-off, horizontal landing

INTRODUCTION

With the advent of commercial space launch vehicles and the drive towards a balanced federal budget, government financial participation in the space launch industry has significantly declined. In order to finance new programs and facilitate the advancement of technologies necessary to travel in space, private capital investment is needed. The growth in market demand for launch services has attracted the interest of private investors. However, commercial investors require a high rate of return on their investments in order to take on the risk associated with these types of programs. In order to attain the necessary capital investment required to initiate new programs, it is essential that designers incorporate financial assessments into the conceptual design phase. These assessments not only need to include the economic outlook of the project, but also to include the risk associated with the assumptions made in the projection.

One methodology used in calculating the financial costs of advanced space launch vehicle designs employs parametric cost estimates. It has been determined that parametric cost estimates allow for greater speed, accuracy, and flexibility in performing these assessments than derived from using other estimating techniques.[1] Parametric cost estimates use cost estimating relationships (CER) and relevant mathematical algorithms to determine cost estimates.

A cost estimate is not expected to precisely predict the actual cost of a launch vehicle program, however it should provide a realistic basis for evaluating the project. The cost analyst should work towards the goal of "cost realism," which is a term used to describe the items that make up the foundation of the estimate. These include the logic used in developing the model, the assumptions made about the future, and the reasonableness of the historical data used in determining the estimate. By analyzing the effects of uncertainty inherent in the predicted value, the analyst is able to determine a more realistic view of the appropriateness of the results.

Parametric models have been developed for assessing the financial viability of advanced space vehicle launch programs. To create this type of model, certain simplifications must be made. These simplifications result in modeling uncertainties that translate into risk when trying to produce a realistic estimate of the financial feasibility of a project. This study analyzes and quantifies the risk associated with two of the assumptions made in performing this type of assessment for two representative conceptual launch vehicles. This includes the market variability of predicting future demand inherent in any commercial market and the uncertainty in determining accurate weight estimates.

TOOLS

The tools used in this research include CABAM (Cost and Business Analysis Module) and Crystal Ball. CABAM is a tool that utilizes parametric economic analysis to determine the financial feasibility of advanced space launch vehicles. Crystal Ball utilizes Monte Carlo simulation techniques to determine the possible outcomes when variability is introduced into the problem. By combining these two tools, an analysis of the effects of variability in weight and market parameters was completed.

Background on CABAM

CABAM was developed at Georgia Tech in response to the need to have a tool that provides a financial assessment of a conceptual launch vehicle design. This tool incorporates not only the life cycle cost attributes associated with a project, but also identifies the potential revenue streams and projects several different evaluation metrics including net present value (NPV), internal rate of return (IRR), and return on investment (ROI).

CABAM is a Microsoft Excel® workbook based simulation tool developed for the analysis of conceptual space launch vehicles. It requires the user to input basic launch vehicle system definitions through component weights and economic parameters such as inflation rate, interest rate, and tax rate. Since it only requires these basic inputs, CABAM may be used for an economic assessment at the conceptual design stage.

Annual market size and market capture percentage for a launch vehicle simulation are determined from key market price variables supplied by the user. CABAM is a fiscal based analysis tool that utilizes fixed rates for all of its economic parameters for the entire life of the project. Yearly life cycle costs and revenue are generated to provide annual cash flows for the project being evaluated.

A schematic of the structure of CABAM is shown in Figure 1. CABAM has a modular structure that is divided into the major components of life cycle cost and revenue generation. The revenue side of CABAM is divided between the government market and the commercial market, which is then further subdivided between cargo and passenger markets. The life cycle cost side of the program is divided into three sections, non-recurring costs, recurring costs, and financing costs.

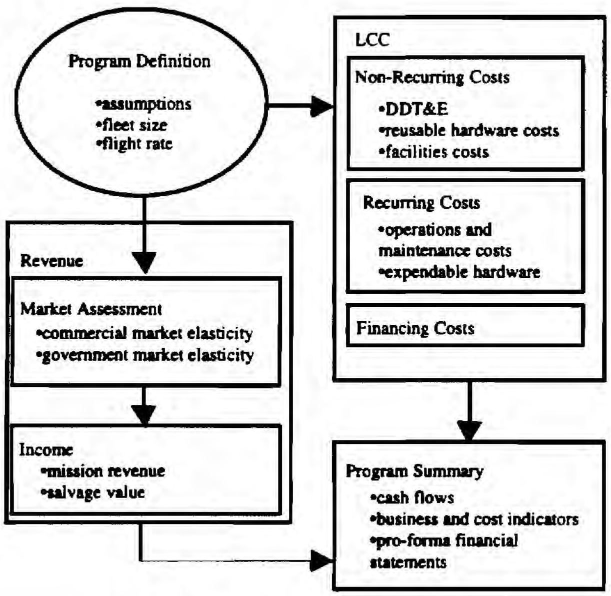


Figure 1: Structure of CABAM

CABAM utilizes elastic market models that were developed during the Commercial Space Transportation Study (CSTS) performed by NASA in 1994.[2] When the user sets the launch prices for each of the four markets, CABAM estimates the market size and share captured and determines the flight rate and required fleet size to accommodate that particular level of market penetration. From this information, yearly revenue streams are calculated.

To determine the total non-recurring cost, CABAM first calculates the design, development, testing, and evaluation (DDT&E) and theoretical first unit (TFU) costs for reusable system components. Weight-based CERs are used to estimate the costs for the vehicle, which are broken down by major subsystems. The CERs are in the form of equation 1.[3]

$$\text{Cost (\$)} = A * W^B * C_f \qquad (1)$$

In the equation, W is the weight of each major component, A and B are constants and C_f is the complexity factor. The A and B values are system component-specific constants obtained from the unrestricted-release version of the NASCOM database for similar component groups.[4] The complexity factor is determined based upon the mechanical and material technology readiness of the components. Overall program wrap factors are also modeled after NASCOM.

Enhancements to CABAM

During the past year, the Space Systems Design Lab (SSDL) at Georgia Tech has continued to upgrade CABAM. The most significant change made was the way in which the model calculates NPV and IRR. The fundamental change was to discount the "free cash flow" of the program, calculated in real dollars, by the real discount rate. This alleviates the problem of having to adjust all future cash flows by the expected inflation rate. The free cash flow is calculated by adding depreciation to earnings before interest and taxes (EBIT) and then subtracting capital investments. By using this method, interest is correctly accounted for in the discount rate and the effect of taxes is removed. This was done to simplify the process of using CABAM in performing a business analysis of an advanced space launch vehicle during the conceptual design phase.

A second major enhancement to CABAM was the addition of detailed pro-forma financial statements. This includes an income statement, a balance sheet, and a cash flow statement broken down by year for the entire life of the program. Along with these upgrades, the user was given greater flexibility in choosing options related to the financing of the program. Included in the newest version of CABAM (version

6.0) is the option to use either level-payment bonds or zero coupon bonds. Also, the user now has the ability to include multiple equity investments made in the project.

Crystal Ball

Crystal Ball® is a user-friendly, graphically oriented forecasting and risk analysis program that provides the probability of certain outcomes.[5] It utilizes Monte Carlo simulation techniques to forecast the entire range of results possible for a given situation. Crystal Ball also provides the confidence levels so that the user will know the likelihood of any specific event taking place.

A Monte Carlo simulation is a system that uses random inputs for key inputs to measure the effects of uncertainty in a model. This is achieved by first specifying the probability distributions for all of the uncertain quantitative assumptions. Next, a random number is generated from the distribution for each parameter to arrive at a set of specific values for computing the output of the simulation run. This process is then repeated numerous times to produce a large number of output values. An approximation of the probability distribution of the output values may be obtained by breaking the range of values into equal increments and counting the frequency with which the trials fall into each increment. As the number of trials increases, the frequencies will converge toward the actual probability.[6]

ANALYSIS

By utilizing the Monte Carlo simulation technique, an analysis of the effects of allowing certain variables to vary within a predetermined range was possible. This study investigated the effects of allowing two variables, the market characteristics and weight estimates to vary within specified ranges to determine the effect on the economic viability of the project.

Calculating Weight Variability

The first step in setting up the analysis was to determine an appropriate methodology for fluctuating weight parameters during the simulation runs. The original vehicle weight statements included a 15% aggregate dry weight margin to allow for weight growth that normally occurs as the vehicle goes through the different stages of design. Since the distribution of the dry weight margin is not known, CABAM uses only the base "best guess" (most likely) component weights to calculate DDT&E and TFU costs, but then applies a 20% cost margin to the final non-recurring cost calculations.

The most-likely weights of the different component groups listed in Table 1 were allowed to vary by the percentages shown in the table. Avionics was allowed to fluctuate equally on either side of the most-likely estimate because of the continual evolution in the development of smaller electronic components compared to the normal weight growth that occurs with all components. The main propulsion was given the greatest allowance on the maximum side because of the complexity of developing new engines for advanced space flight launch vehicles.

Table 1: Variances by Component Group

Component Groups	Minimum	Maximum
Wing Group	-5%	20%
Tail Group	-5%	20%
Body Group	-5%	20%
TPS Group	-5%	20%
Landing Gear	-5%	20%
Main Propulsion	-5%	25%
RCS Propulsion	-5%	10%
OMS Propulsion	-5%	10%
Primary Power	-5%	10%
Electrical Conversion and Distribution	-5%	10%
Surface Control Actuation	-5%	10%
Avionics	-10%	10%
Environmental Control	-5%	10%

CABAM was reconfigured to allow for adjustments to be made in the size of the payload capacity depending on the total combined weight of the components in comparison to the original dry weight of the vehicle. Therefore, if the new dry weight of the vehicle calculated *after* the components weights were randomly changed per Table 1 exceeded the original baseline weight (including its 15% dry weight margin), the difference was then subtracted from the payload capacity, thus reducing revenue for each launch. The opposite also held true: if the new weight was less than the original weight, then the payload capacity was increased resulting in additional revenue.

For passenger missions, incremental changes in the number of passengers carried per flight were only permitted for increments of 1800 lbs. It was assumed that each passenger would generate that amount of weight growth in the different systems required to transport a human into space.

As shown in Figure 2, a triangular distribution was placed on each of the component groups for the Monte Carlo simulation. The minimum and maximum weights allowed were calculated based upon the percentages listed in Table 1.

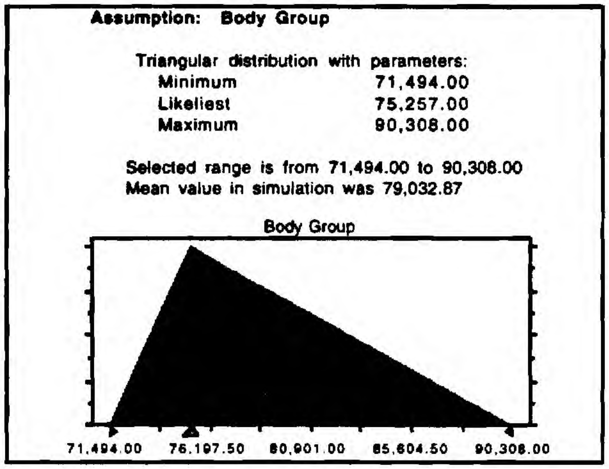


Figure 2: Representative Triangular Weight Distribution

Calculating Market Volatility

To evaluate the sensitivity of the model to changing market conditions, an approximation of the volatility of demand was assumed. The authors estimated that greater volatility exists in the lower price segments compared to that occurring in the higher price market. The reason for this estimation was based upon the fact that market demand is already known for higher price segments based upon current market conditions, thus lower risk exists for competing in this price range. As shown in Table 2, it was assumed that at the lower price segment, a 30% fluctuation in the size of the commercial market and a 15% fluctuation in the size of the government market may exist from current estimations. At the higher price segment, a 5% fluctuation was included for both markets.

Figure 3 shows the market estimations for commercial cargo, which was one of four markets used in this study. The solid line represents the baseline case and the long dash lines represent the variability possible in market demand. This graph depicts the tapering of market variability as the price increases.

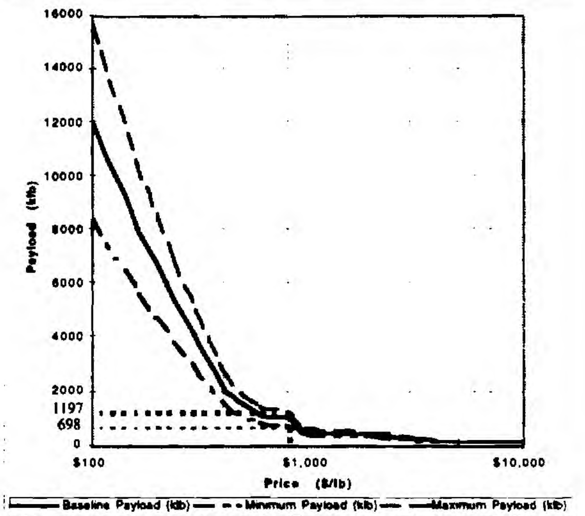


Figure 3: Commercial Cargo Market

Two equations were derived to determine the size of the market captured under the predefined assumptions. By using these equations, the market volatility was quantified for a specified price. For the commercial cargo market, the market demand fluctuated between 1,197,000 lb. and 698,000 lb. at a price of $820/lb. as shown in Figure 3 by the horizontal dotted lines. The first equation gives the

Table 2: Prices and Market Fluctuation for Each Market Segment

	Price				Market Fluctuation	
Market Segment	Units	Optimal	High	Low	High	Low
Commercial Cargo	$/lb	820	5,000	100	30%	5%
Commercial Passengers	M$/passenger	0.52	5.0	0.2	30%	5%
Government Cargo	$/lb	1,650	5,000	100	15%	5%
Government Passengers	M$/passenger	7.12	15.0	0.2	15%	5%

total demand in pounds for the market.

$$F * S * B + B = M \qquad (2)$$

In equation 2, F is the factor that is allowed to vary between 1 and −1 during the Monte Carlo simulation creating the effect of either being greater than or less than the expected value. As shown in Figure 4, a triangular distribution was placed on F for the simulation run. B is the base value of the market demand determined by the price. S is the scale factor that fluctuates linearly between 5% and 30% for the commercial market and between 5% and 15% for the government market depending on the price. The result of this equation, M, is the net market size captured by the particular project under evaluation.

$$S = S_2 - \frac{S_2 - S_1}{P_2 - P_1}(P_2 - P) \qquad (3)$$

Equation 3 was used to calculate S for equation 2. P is the price to launch either a pound of payload or one person into low earth orbit (LEO). For each of the four market segments, the price was set at a previously determined optimal level to achieve the maximum rate of return for the program (Table 2). A grid search optimization strategy was used to determine the optimal pricing strategy for this class of vehicles.[7]

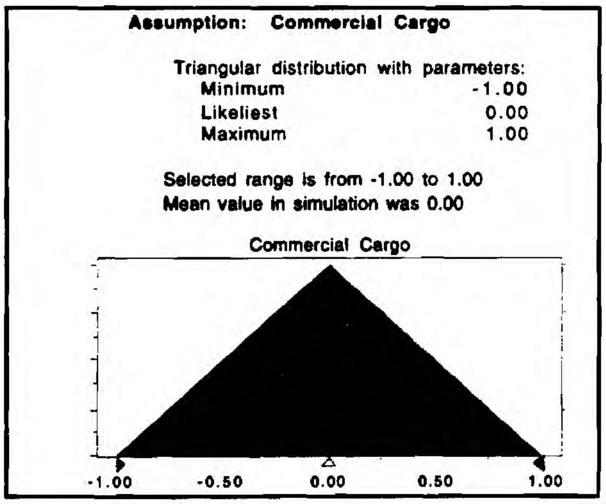


Figure 4: Representative Triangular Market Distribution

The prices used in the analysis are shown in Table 2. P_1 is the price at the lower bound and P_2 is the price at the upper bound. These bounds are represented by the high and low figures also shown in Table 2. S_1 is the maximum fluctuation allowed in the market and S_2 is the minimum fluctuation allowed. These percentages are also shown in Table 2.

Sample Vehicles

To provide analysis data for this research, two candidate single-stage-to-orbit (SSTO) reusable launch vehicle (RLV) designs were chosen to serve as reference vehicles. For both vehicles, the initial operating capability (IOC) was projected to be 2008 and steady state operation was assumed for the period from the year 2010 to 2025. The baseline case for the two vehicles had a cargo capacity of 44,000 pounds or twenty-four passengers.

The first concept selected, which takes advantage of more off-the-shelf technologies, was an all-rocket SSTO vehicle with vertical take-off and horizontal landing (VTHL). This concept, which utilizes five LOX/LH2 rocket engines, is shown in Figure 5. Each vehicle was configured to allow for cargo and passenger service to low earth orbit (LEO, due east from KSC).

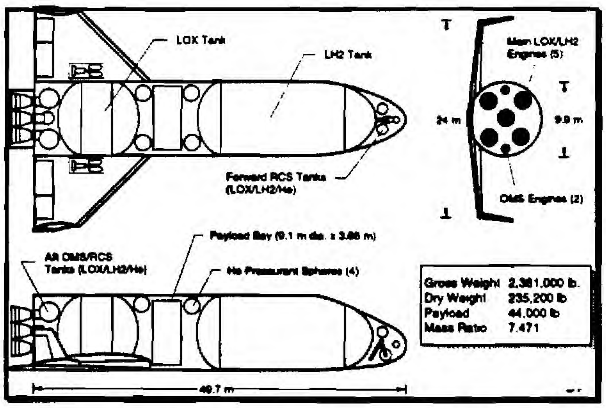


Figure 5: SSTO All Rocket Vehicle

The second concept, an advanced launch vehicle named *Hyperion*, is currently being investigated by students in the SSDL at Georgia Tech. This concept, shown in Figure 6, represents a RLV with horizontal take-off and horizontal landing (HTHL). The

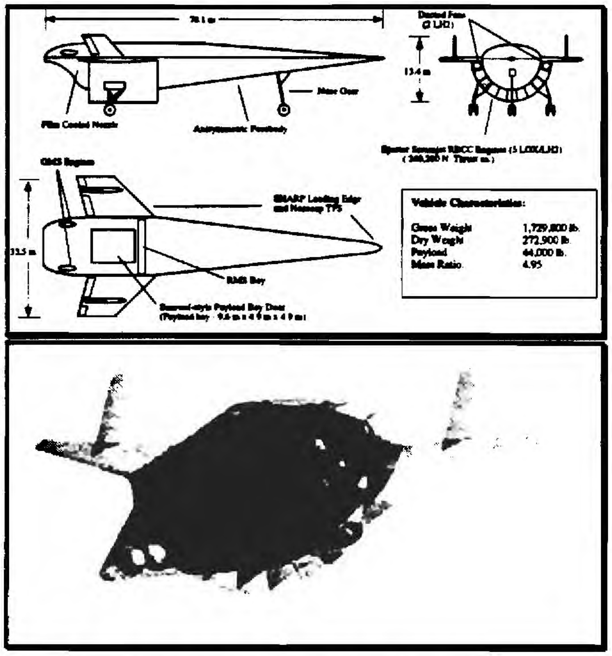


Figure 6: *Hyperion* Vehicle

propulsion system of this vehicle consists of five LOX/LH2 ejector scramjet (ESJ) rocket-based combined–cycle (RBCC) engines.[8]

The technology readiness level (TRL) for the *Hyperion* vehicle was much lower than the all rocket vehicle mainly because of the use of RBCC engines. This resulted in higher complexity factors for *Hyperion* compared to those used for the other vehicle. Since *Hyperion* utilizes a horizontal take-off, larger landing gear, wings, and tail were required. These factors resulted in an overall heavier dry weight for *Hyperion*.

RESULTS

Using Crystal Ball, a Monte Carlo simulation of 5000 trails was run for each vehicle with the pre-defined assumptions. The results show that the model was more sensitive to changes in the market parameters than to changes in the weights. As Figure 7 and Figure 8 show, the highest correlation existed between the economic indicators, in this case NPV, and the commercial cargo market.

These charts show that market volatility exerted greater influence over the financial outcome of the project compared to fluctuations in weight parameters. Specifically, changes in the demand for the commercial cargo market had the greatest impact upon the economic viability of an advanced space launch vehicle program under the parameters set forth in this analysis. This was a common result for both vehicles, however the results for weight parameters differ between *Hyperion* and the all-rocket vehicle.

For the weight parameters, the results corresponded with the weight breakdowns for the vehicles in terms of significance. For *Hyperion*, the body, wings, landing gear, and main propulsion

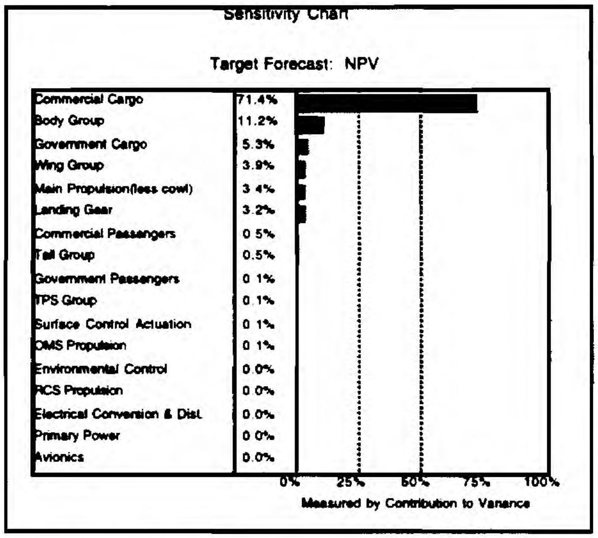


Figure 7: Sensitivity Chart for *Hyperion*

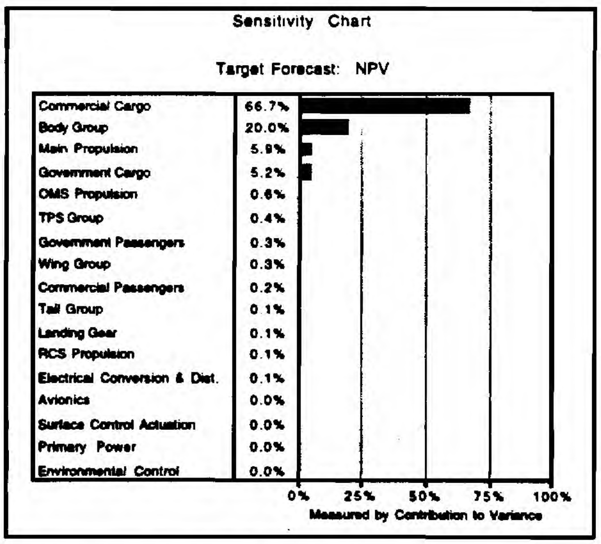


Figure 8: Sensitivity Chart for Rocket Vehicle

system were the most significant in terms of weight requirement. From this information, the economic validity of utilizing horizontal take-offs might be questioned due to the need for heavier components that result from this feature.

For the rocket vehicle, the body and the main propulsion system were the most significant. Therefore, designers could infer from these findings that changes in the weight of the body group would have a significant impact upon the financial outlook of the design. Conversely, improvements in the weights of avionics, surface control actuation, primary power, and environmental control would have minimal impact upon the profitability of the overall program.

The results for the two vehicles broken down by economic indicators, NPV and IRR, are shown in Figure 9. The charts depict the frequency distributions for each vehicle, with the corresponding statistics listed below each of the charts. The statistics highlight the important findings from each of the simulation runs.

The NPV showed a variability of +-50% of the mean value for both vehicles. The rocket vehicle had a slightly higher average than *Hyperion* and a slightly lower standard deviation. Based upon these findings, the rocket vehicle would be a superior investment because of the higher return coupled with the lower risk value. However, the difference in return between these two vehicles was marginal. The simulation runs for the forecast value IRR resulted in the exact same standard deviation for both vehicles. As a percentage of the mean value, the standard deviation was approximately 6% for both simulations. These statistics show that by varying the weight and market parameters by the values defined previously results in significant volatility in the financial outcome of the project.

Reward-to-Variability Ratio

In performing a financial analysis of a project, it is imperative that the reward be taken in context with the amount of risk assumed. The Sharpe ratio is an economic indicator that combines both factors into a single metric. Introduced in 1966 by Professor William Sharpe of Stanford University, the Sharpe ratio was intended to measure the performance of mutual funds. It has gained considerable popularity in the financial community as a metric for comparing different investments. As shown in equation 4, to arrive at the Sharpe ratio, the risk-free rate, r_{rf}, is subtracted from the average return of the project, which is then divided by the standard deviation of the return, $\sigma(x)$.[9]

$$SR(x) = \frac{\bar{r}(x) - r_{rf}}{\sigma(x)} \tag{4}$$

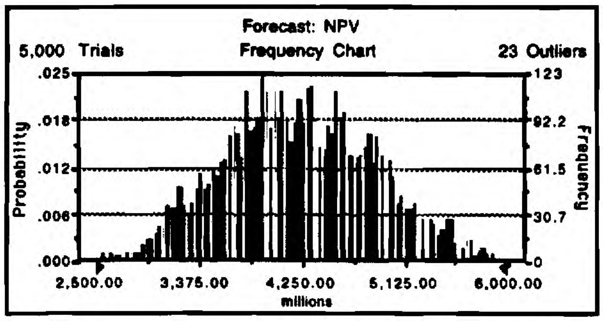
For illustration purposes, the Sharpe ratio of a portfolio held from 1954 to 1994 containing shares from all stocks with a market capitalization over $150 million was 43.[10] From the analysis, the Sharpe ratio was calculated for *Hyperion* as a somewhat disappointing 7.2 and for the all rocket SSTO vehicle as 7.3 using a risk-free rate of 5.27% as shown in Table 3.[11] The risk free rate was derived from the current yield on 30 year government bonds. In terms of the Sharpe ratio, higher numbers indicate better risk-adjusted returns.

Table 3: Values Used in Sharpe Calculation

	r_{rf}	$\bar{r}(x)$	σ	SR(x)
Hyperion	5.27%	9.65%	0.61%	7.2
Rocket	5.27%	9.75%	0.61%	7.3

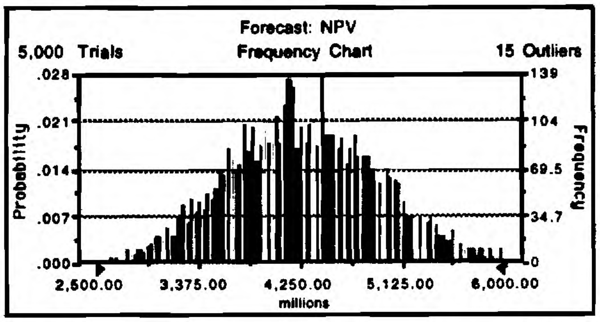
The 30 year government bond yield was chosen because it contains no default risk and matches the term in years of the launch vehicle program. It might be argued that a shorter term government security would eliminate interest rate risk, which should not be included in the calculation of the Sharpe ratio for this type of analysis. However, short-term government securities do not reflect expected long run changes in inflation. Therefore, there is a trade-off in using either rate, but the overall implications to the value obtained from the Sharpe ratio calculation are marginal.

Hyperion

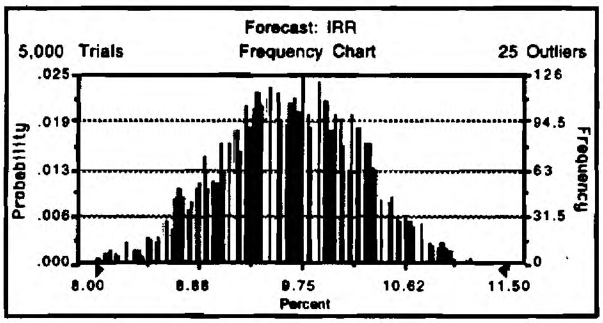


Statistics:	Value
Trials	5000
Mean	4,231.28
Median	4,220.15
Mode	---
Standard Deviation	653.06
Variance	426,488.36
Skewness	0.05
Kurtosis	2.74
Coeff. of Variability	0.15
Range Minimum	1,657.69
Range Maximum	6,279.83
Range Width	4,622.14
Mean Std. Error	9.24

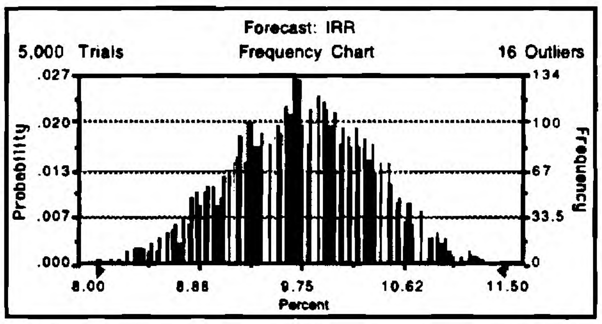
Rocket



Statistics:	Value
Trials	5000
Mean	4,282.63
Median	4,271.14
Mode	---
Standard Deviation	635.96
Variance	404,440.04
Skewness	0.06
Kurtosis	2.74
Coeff. of Variability	0.15
Range Minimum	2,123.13
Range Maximum	6,344.48
Range Width	4,221.35
Mean Std. Error	8.99



Statistics:	Value
Trials	5000
Mean	9.65
Median	9.67
Mode	---
Standard Deviation	0.61
Variance	0.37
Skewness	-0.17
Kurtosis	2.90
Coeff. of Variability	0.06
Range Minimum	6.85
Range Maximum	11.38
Range Width	4.53
Mean Std. Error	0.01



Statistics:	Value
Trials	5000
Mean	9.75
Median	9.76
Mode	---
Standard Deviation	0.61
Variance	0.38
Skewness	-0.17
Kurtosis	2.84
Coeff. of Variability	0.06
Range Minimum	7.39
Range Maximum	11.51
Range Width	4.12
Mean Std. Error	0.01

Figure 9: Comparison of Results for Both Vehicles

In this analysis, the results of using the Sharpe ratio only quantify the risk associated with market volatility and variances in the weight parameters of the different components. Many other factors create risk in this type of project that might adversely or positively affect the financial viability for an advanced space launch program. Therefore, the identification of the Sharpe ratio obtained by a stock portfolio in a previous paragraph was not meant as a comparison to the results obtained from the two vehicles, but rather to provide an illustration of the numeric values expected.

DISCUSSION

In the analysis section, the Sharpe ratio was introduced as a metric that might be used for the financial analysis of advanced space launch vehicle programs during the conceptual design phase. This ratio was originally developed for the sole purpose of evaluating mutual funds based upon past performance. Experts in the field might question the validity of using this ratio for the purposes outlined in this paper. It has been suggested that derivatives of the equation might be preferable for this type of evaluation.

A possible alternative for equation 4 would be to eliminate the use of the risk free rate, thereby dividing the average return by the standard deviation. This would result in values of approximately 16 for the two vehicles analyzed in this paper. It has also been suggested that average return should be divided by the standard deviation squared. This would raise the value to approximately 26 for *Hyperion* and the rocket vehicle. These two derivative equations would simplify the process for the conceptual designer as well as eliminate the controversy associated with determining an appropriate value for the risk free rate.

If the relationship between the *total* economic risk of the project and the risk associated with the two factors considered in this paper (i.e. component weight and market variability) was known, then a scale factor could be applied to the ratio. This would provide a result that could be used in a comparative environment with other launch programs as well as other investment projects.

CONCLUSIONS

The goal of this research was to investigate the effects of uncertainties associated with weight and market parameters in determining the economic viability of advanced space launch vehicles. Market sensitivity and weight-based cost estimating relationships are key drivers in determining the financial viability of a project. The expected uncertainty associated with these two factors drives the economic risk of the overall program. Monte Carlo simulation techniques were incorporated into the analysis to determine the sensitivity of the model to changes in market and weight parameters. From this, the risk generated by the variability of these two parameters was quantified.

From the findings of the Monte Carlo simulations, it may be concluded that the volatility of the market will play an integral role in the viability of commercial advanced space flight vehicle programs. These findings emphasize the importance of the need for accurate market demand forecasts. For weight parameters, the results suggest that certain component groups, depending on the vehicle type, dominate others in terms of significance to the overall economic viability of a launch program. From this, it may be concluded that improving the accuracy of the estimates of weight for certain component groups will minimize the risk associated with weight estimations.

In addition to these findings, a metric was introduced which would quantify the risk as it relates to the return of the project. This provides designers with a basis from which to work in identifying the value of different factors that may affect the financial outcome of an advanced space flight program. In terms of weight estimations, by improving the confidence level of the predictions made about the weights of specific components, the Sharpe ratio may be increased for the whole program, thereby improving the financial viability of the design. Utilizing CABAM and Crystal Ball, further investigations may be made into other factors that create uncertainty in the financial outlook of space launch vehicles.

From the analysis, it was determined that the all-rocket SSTO vehicle was a slightly better investment due to the higher Sharpe ratio. In terms of IRR, both vehicles displayed the same risk value for weight and market parameters as a whole, however the rocket vehicle had a slightly higher return. Since the analysis was performed at a conceptual design stage, the difference in the financial viability was marginal and should not be a determinant in choosing between the two vehicles at this stage of development. It should also be noted that the analysis was performed based upon subjective assessments of weight variability and market volatility (Tables 2 and 3). With those assumptions and the CSTS launch market assumptions also used, neither vehicle results in a particularly attractive economic scenario for potential investors.

FUTURE WORK

Future work for this research may include the investigation of other factors that might affect the economic viability of a launch program. This would include not only items directly related to the design of a vehicle, but also economic factors and government incentive programs that could have far reaching implications for the advancement of space flight.

Other possible areas of interest for this type of investigation might include the analysis of targeted marketing efforts. Certain areas of the market may provide a higher level of stability for commercial launch service providers, but at what cost to return? For example, if a launch service concentrated solely on the government passenger market, the risk would be significantly reduced, however the return might be considerably lower, thus resulting in an overall lower quality project in terms of financial viability.

An expansion upon the use of the Sharpe ratio in determining the economic performance of advanced space launch vehicle programs might be another area of consideration for investigation. The intention here would be to try to incorporate and quantify the total risk of the program, thereby providing a metric for use in the comparison of alternative launch programs.

CABAM will continue to be improved by expanding upon the modules within the model and by adding new components to the overall structure.

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